

UNITED STATES AIR FORCE ARMSTRONG LABORATORY

Technology Options for Modular Ground Support Equipment

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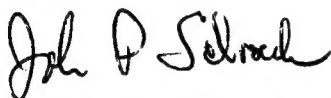
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JOHN P. SCHROEDER, 2Lt, USAF
Contract Monitor



for BERTRAM W. CREAM, Chief
Logistics Research Division

PREFACE

This report describes technologies relevant to design of new aerospace ground equipment. The Logistics Research Division has begun work in this area under the title of Modular Aircraft Support System (MASS) and Work Unit 2940-03-15. A number of candidate materials and mechanical engineering innovations were identified during the survey, and alternative combinations of them were examined. The study was limited in scope; it was intended to provide a broad overview of general design choices. The analysis of these choices is carried forward in related work under the MASS program, specifically in the creation of a QFD House of Quality defining MASS configuration options. Even so, there seemed to be enough here of general interest to warrant a stand-alone summary of the broad technology choices for MASS as well as other types of advanced aircraft support equipment. The work unit scientist is 2nd Lt. John Schroeder.

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13. ABSTRACT (Maximum 200 words)

Advantages and disadvantages of various technologies applicable to design of aircraft ground support equipment are described. The target system is a multifunction power cart of modular design able to support a variety of military aircraft with electrical, cooling air, pressured air, and hydraulic power to support servicing and maintenance. Existing technologies for each design option are compared with each other and against the requirement to provide affordable solutions for new design approaches for ground support equipment. The report identifies a set of technologies expected to be best suited to these purposes over the next four years.

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Executive Summary

This report describes the work done and the results obtained during Subtask 1, Technology Assessment, of the Modular Aircraft Support System (MASS) Design Supportability Studies program. The program consists of several front-end studies to define a technology baseline that can be used as the basis for design choices for MASS.

The Technology Assessment consisted of a technology information gathering effort and an evaluation of the technologies identified. A list of engineering domains pertinent to MASS was first identified and then used as the basis for information and literature searches. These searches included both government and industrial sources as well as conversations with personnel familiar with ground support equipment.

The information obtained from these searches was then evaluated, and the advantages and disadvantages of the technologies relative to MASS were specified. The criteria used in the technology evaluation effort were performance, deployability, environmental impact, supportability, user needs, and affordability. Finally, the technologies that could be used best in MASS were documented in this report.

As a result of this subtask, the following technologies are recommended for consideration in MASS:

- (1) Engines - Small Turbine Engines, Diesel Engines
- (2) Motors - AC Induction Motors
- (3) Air Conditioning Equipment - Vapor Compression, Air Cycle
- (4) Energy Conversion - Synchronous AC Generators
- (5) Hydraulic Pumps - Piston Pumps, Gear Pumps
- (6) Air Compressors - Reciprocating Piston Compressor
- (7) Floodlights - High Pressure Sodium
- (8) Nitrogen Generation - Hollow Fiber Membrane
- (9) Batteries - Totally Sealed Thin Metal Film Lead Acid, Sealed Lead Acid
- (10) System Controls - Built-in-Test (BIT) Detection
- (11) Engineering Materials - Steel, Aluminum

List of Acronyms and Definitions

Absorption, Heat of - The heat released by certain pairs of compounds that bind together chemically when mixed.

AC - Alternating current. A method of delivering electrical energy in which the polarity oscillates with sinusoidal variation, reducing net current flow, and subsequent transmission losses.

Adiabatic Efficiency - The relative performance of a real system to an ideal system in which no heat is lost.

Adsorption - The chemical attraction of a substance to a solid surface.

AGE - Aerospace Ground Equipment.

Ah - Amp-Hour

AHE - Absorber Heat Exchange.

Ambient - The surrounding conditions, especially temperature, in which a piece of equipment is operating.

Amp, Ampere - The unit of electrical current.

APU - Auxiliary Power Unit.

Armature - A moving part in a motor or generator where mechanical energy is converted to electrical energy.

Bipolar - Any electrical or magnetic system with positive and negative terminals.

BIT - Built-in-Test.

Boundary Layer - Slow-moving fluid that builds up around a solid body due to friction, whenever a solid body moves through a fluid media, or fluid flows over a stationary surface.

Brushes - Small copper tabs that slide over each other, sequentially closing different electrical circuits inside rotating electrical machinery.

BTU - British Thermal Unit.

Capacitor - An electrical energy storage device that is often used to shift the phase angle of an alternating current signal.

Catalyst - A chemical substance which, when present, encourages other chemicals to react with each other.

CFC - Chlorofluorocarbon.

cfm - Cubic feet per minute. A unit of volumetric flow measurement usually used for compressible gases such as air.

COLORS - Contingency Operations Logistics Requirements.

Combustor - The section of a gas turbine engine in which combustion takes place.

Commutator - A device for reversing the direction of electrical current.

COP - Coefficient of Performance.

Core Loss - The loss of energy caused by resistance to magnetic flux. This is analogous to resistive losses caused by the flow of electrical current.

Critical Point - The temperature and pressure condition above which no distinction can be made between liquid and vapor phases of a fluid.

Current - The flow of electrical charge caused by an electromotive force (voltage).

DC - Direct current. Method of delivering electrical energy in which current flows in only one direction.

DoD - Department of Defense

DARPA - Defense Advanced Research Projects Agency

Diffusion - The migration of one substance into another caused by the constant vibrational motion at the molecular level.

Diode Rectifier - A circuit element that uses an arrangement of semiconductors, which permit current to flow in only one direction, to convert alternating current into direct current.

DTIC - Defense Technical Information Center.

Dynamic Compressor - A type of compressor that accelerates a gas and then allows inertia to convert kinetic energy (velocity) into pressure. This type of compressor delivers varying performance depending on the upstream and downstream conditions.

Electrical Current - *See Current.*

EMAGE - Electric Multifunction Aerospace Ground Equipment.

Flash Point - The temperature and pressure condition at which liquid flashes into vapor.

Fouling - The degradation of heat exchanger performance caused by the restriction of flow passages.

Frequency - The rate at which an alternating current reverses polarity.

Galvanizing - Electroplating with zinc to improve corrosion resistance.

GAX - Generator Absorber Heat Exchange.

Glow Plug - An electrically heated member located in diesel engine cylinders that encourages the onset of combustion by locally raising the temperature of the compressed fuel-air mixture.

GSE - Ground Support Equipment.

HCFC - Hydrochlorofluorocarbon.

Heat Capacity - The heat required to raise the temperature of a unit mass of a substance by one degree.

Hermetic Seal - An airtight, watertight seal that prevents the interaction of fluids or excludes combustible gases from a spark-producing system.

HFC - Hydrofluorocarbon.

HID - High Intensity Discharge.

H_z - Hertz (cycles per second).

HP - Horsepower. A traditional unit of power measurement equal to 746 watts.

IAC - Information Analysis Center.

IC - Internal Combustion.

Ions - Charged molecules that conduct electricity by their movement until they combine with an ion of opposite charge.

IPPD - Integrated Product Process Design.

KVA - Kilovolt-ampere. The metric unit for three-phase electrical power. Numerically equivalent to kW in single phase applications.

kW - Kilowatt. 1000 watts. The metric unit for power. 746 watts are equivalent to one horsepower.

Latent Heat - The heat released (or required) to cause a liquid to change phase (freeze or boil).

Lean Blowoff - The escape of unburnt fuel into the exhaust of an engine.

LHE - Liquid Heat Exchange.

LRU - Line Replacement Unit.

Lumen - A unit of light intensity measurement.

Magnetic Flux - The magnetic equivalent to electric current. Coils of wire can temporarily convert electric current into magnetic flux.

MASS - Modular Aircraft Support System.

MPT - Manpower, Personnel, and Training.

NBC - Nuclear, Biological, and Chemical.

PEM - Polymer Exchange Membrane.

PEMFC - Polymer Exchange Membrane Fuel Cell.

Polyphase Circuits - AC electrical circuits that provide multiple alternating signals, usually three phases 120 degrees apart, allowing more power to be transmitted without proportionally raising voltage or current levels.

Positive Displacement Compressor - A type of compressor that traps a volume of low pressure fluid and delivers it to a high pressure region, sometimes after reducing the volume of the trapped fluid.

Power Factor - The ratio of available electrical power to total power in a three-phase circuit.

PPM - Parts per Million.

Pressure Ratio - The ratio of highest pressure to lowest pressure regularly achieved in a system operating in a closed thermodynamic cycle.

PSA - Pressure Swing Absorption

psi, psig - Pounds per square inch. A unit of pressure measurement. Psig indicates that the pressure measurement is relative to atmospheric pressure.

R&M - Reliability and Maintainability

Regenerative Cycle - An open loop thermodynamic cycle modified so that hot exhaust gases give up some of their heat to colder intake fluid streams.

Rotor - The rotating member of a motor or generator that connects to the shaft and contains electrical coils that interact with those of the stator.

SIDAC - Supportability Investment Decision Analysis Center.

Stator - The stationary part of a generator or motor that interacts electromagnetically with the rotor.

Synchronous Generator - A constant speed machine that produces alternating current of a frequency proportional to its rotational speed.

THD - Total Harmonic Distortion.

TMF - Thin Metal Film.

Ton (of refrigeration) - A traditional unit of cooling load equal to 12,000 Btu/hr or 3.52 kW.

Torque - The energy available for twisting a shaft. Torque is measured in ft-lbs or N-m.

TWISTIAC - Tactical Warfare Simulation Technology Information Analysis Center.

V - Volt.

Volatile Organic Compounds (VOCs) - Hazardous airborne chemicals that are released during the burning of fossil fuels and certain other processes.

Volatile Liquids (fuels) - Combustible liquids that evaporate easily, and increase the risk of explosions if their vapors migrate toward an open flame or spark.

Volt - The unit of electromotive force. Electromotive force causes current to flow through an electrical resistance.

VRLA - Valve Regulated Lead Acid.

Waste Heat - The heat present in the exhaust streams of open loop systems which can sometimes be recovered to improve thermal efficiency.

Watt - The metric unit for power. 746 Watts are equivalent to one horsepower.

Wh, kWh - Watt-hour and kilowatt-hour. Units of energy defined by the use of a watt or kilowatt for one hour.

MASS Design Supportability Studies

Subtask 1: Technology Assessment

1.0 Introduction

The Logistics Research Division of Armstrong Laboratory (AL/HRG) has begun a research effort to improve the reliability, maintainability, operability, and deployability of support equipment in general, with a specific emphasis on Aerospace Ground Equipment (AGE). The overall goal of this research is to create affordable solutions that shorten the "logistics tail" while improving the usefulness and deployability of the equipment. As part of this effort, AL/HRG has begun a research program to define the requirements for and evaluate the feasibility of a family of equipment to support a Modular Aircraft Support System (MASS).

As the MASS name implies, the modular concept would combine several servicing and maintenance utilities in a few versatile carts. Currently, aircraft requirements for such utilities as electrical and hydraulic power, compressed air, and cooling air are provided by single-function carts that share very few common parts. The MASS program will improve upon the existing AGE by consolidating these utilities into reconfigurable multi-function carts. In addition, the affordability, reliability, maintainability, and operability of the units will be improved by using current technologies versus the 1960-era technologies used in some existing carts.

The improved packaging concept should decrease the deployment footprint by minimizing the number of frames, engines, and gas tanks required to support the operational mission. Additionally, improved reliability and maintainability as well as a common core set of parts should reduce the number of spare parts required and increase the availability of the AGE carts. The common core set of parts should also help reduce any AGE proliferation problems and the modularity of the systems should ensure flexible and affordable initial purchase and upgrade options.

This report describes a technology assessment for the MASS concept. Together with other front-end studies, this effort attempts to define a technology baseline that can provide the basis for choices for MASS.

1.1 Objective

The objective of this subtask was to identify and assess available or emerging technologies that could be used in a MASS design in a variety of engineering domains. Those technologies that met the requirements of MASS would then be used in the trade study within the third subtask where they would be further evaluated as part of the MASS concepts.

1.2 Scope

The scope of this subtask was to perform a broad technology identification and assessment based on anticipated MASS requirements. We looked at work in industry and government labs, located relevant scientific and engineering studies and reports, and studied current and planned products within the AGE community. This helped to identify relevant products, processes, and materials; examine their advantages and disadvantages from a MASS design viewpoint; and document sound results. The assessment was not intended to be comprehensive from a purely technological viewpoint, nor to deal with projected technology developments in the mid- to far-term future. We wanted to identify and assess current and near-term technologies within our constrained domain. This domain included developing a MASS technology demonstration within five years (by the year 2000). It also included technologies that would fulfill the output ranges needed to meet projected MASS requirements. These requirements were identified in conjunction with another AL/HRG research effort and catalogued in the Contingency Operations Logistics Requirements (COLORS) database. The identification process included a review of existing AGE capabilities (supply) as well as existing and anticipated aircraft servicing requirements (demand). Table 1 indicates the capabilities and ranges used as ballpark figures for this study.

Table 1. Scope of Capabilities and Ranges

Capability	Range
Air Compression	50 - 4000 psig @ 15 SCFM
Air Conditioning	0 - 115 lbs /min @ 45 - 200 F
Floodlights	0 - 140,000 lumens @ 0 - 1000 watts
Nitrogen Supply	0 - 600 psig @ 0 - 40 SCFM
Hydraulic Power	0 - 5,000 psig @ 0 - 54 gpm
Electrical Power	0 - 75 KVA @ 120/208 VAC and 400 Hz
Start Air	0 - 51 psig @ 125 lbs/min

2.0 Method

The method used in Subtask 1 to identify candidate technologies used two steps:
(1) Information Gathering and (2) Technology Evaluation.

2.1 Information Gathering

To assess the current and near-term technologies available for possible use in a MASS unit, we developed a list of engineering domains applicable to MASS. This list was based on information provided in the Statement of Work and associated background materials, discussions with equipment and human factors engineers, and a visit to the Springfield Air National Guard Base AGE Maintenance Shop. Both currently-available technologies and emerging technologies were considered. The requirement established for new technologies was that they be available for demonstration by 1997. The following list formed the basis for the literature search and information gathering efforts:

- Engines
- Air Conditioning Equipment and Refrigerants
- Electrical Generators
- Electrical Power Conditioning and Converters
- Batteries/Fuel Cells
- Air Handling Equipment and Compressors
- Hydraulics
- Nitrogen Generation Equipment
- Floodlight Equipment
- Materials, including Composites
- Alternative Fuels
- Environmental Compliance Techniques

- Fault Monitoring, Built-in-Test, and Diagnostics
- Modular Design Concepts
- System Reconfiguration Concepts
- Reliability Improvement, including Redundancy
- Maintainability Innovations.

Data-gathering efforts concentrated on the domains described above. Both government and industrial sources were surveyed. These included the Defense Technical Information Center (DTIC) and the Information Analysis Centers (IACs) that it sponsors, including the Tactical Warfare Simulation Technology Information Analysis Center (TWISTIAC), the Metals Information Analysis Center, the Manufacturing Technology Information Analysis Center, the Reliability Analysis Center, and the Supportability Investment Decision Analysis Center (SIDAC).

Wright Laboratory was surveyed and the members of the Air Force AGE community were consulted on current programs that are applicable to MASS. DTIC's current program descriptions were searched for programs throughout the Department of Defense (DoD) and its contractors. *Partnerships: A Compendium of State and Federal Cooperative Technology Programs* was consulted to find additional sources of applied technology information.

Government sources such as the National Technical Information Service, the Defense Advanced Research Projects Agency (DARPA), the National Science Foundation, the Office of Technology Transfer, and the National Institute of Standards and Technology's Advanced Technology Program were searched on-line. Data in technical journals were searched using the Applied Science and Technology Index, Compendex, and Medline. Industry information was surveyed using personal catalog files of technical personnel and by contacting companies identified through the *Thomas Register* and Internet home page searches using InfoSeek. In addition, industrial sources and magazines such as *GSE Today* and *Aviation Week and Space Technology* were reviewed for pertinent articles.

2.2 Evaluation of Technologies

Each of the technology areas necessary for the fabrication of MASS units include several technologies that could be used. As part of this task, these technologies were evaluated to determine the potential for each technology to meet MASS criteria. This evaluation was conducted by applying several evaluation criteria as described below.

The criteria used in the MASS evaluation effort were performance, deployability, environmental impact, supportability, user needs, and affordability. These criteria are defined as:

Performance - This criterion includes how well the technology meets the performance needs of the MASS. The output and efficiency of the technology are important parts of this evaluation criterion. Some technologies are inherently better at certain output ranges than at others. Accordingly, if that output range is what is needed for MASS, that technology would be better for MASS than others. The efficiency of some technologies in these ranges is also better than others and would be for MASS.

Performance also includes how well the technology endures extremes of temperature, humidity, vibration, and so forth. These extreme environments also could include the effects of nuclear, biological, and chemical (NBC) contamination and decontamination. Thus, a technology that can be used for MASS and would withstand extreme environments is better than one that would not.

Finally, performance also includes the maturity and development potential of the technology. A new, untried, and usually expensive technology may be less valuable as part of MASS than another, more mature and less expensive technology. However, a new technology with the potential to provide a capability to the MASS at a much lower weight than an off-the-shelf technology might be more highly rated.

Deployability - This is the primary impetus for MASS. Current AGE machines designed on the "one machine, one function" principle impose a high airlift penalty for deploying air forces. In contrast, modular AGE designs permitting a "one machine, many function" approach

would reduce airlift weight and volume. Hence, technologies that promote lighter and less bulky machines were of interest. Since the MASS will be transported within a C-141 or similar aircraft, a technology that can be built tall and thin rather than wide and flat (a smaller footprint) is preferred, at least up to the height of the aircraft.

Environmental Impact - All military equipment must meet current environmental regulations, and MASS is no exception. The criterion of environmental impact was used to evaluate the capability of each technology to meet these regulations and still perform as required for MASS. Included within this criterion were the presence of hazardous materials, high noise levels, and pollution emitted by this technology. Environmental impact was also considered in light of available compliance techniques. Sometimes, a technology uses an environmentally hazardous material, but in such a way that it meets all applicable environmental standards. Thus, if the technology can be easily kept in compliance, it is not arbitrarily downgraded as compared to other technologies.

Supportability - This criterion includes all of the standard "ilities" including Reliability and Maintainability (R&M) and Manpower, Personnel, and Training (MPT) issues. For each technology, the reliability of the current equipment using that technology was evaluated and compared to other equipment performing the same function. In addition, any foreseeable reliability improvements were studied to determine their effect on evaluation in the future. Maintainability of the equipment was evaluated for current performance and future improvements. The possibility of employing maintainability innovations in the design of the equipment using each technology was also evaluated.

Each technology was evaluated on the likelihood that equipment built using that technology would promote modular design. As for the R&M criteria, the equipment that could be made modular in the future was also considered. Modular design concepts were evaluated while using each technology to determine if a MASS unit built using that technology would benefit from these concepts.

Technical difficulty from a user perspective was also considered. Equipment requiring more training time, more manpower, and/or higher skill levels to operate and maintain would be less valuable than equipment that does not. Ease of maintenance promotes system economy and

readiness by reducing maintenance mechanics and system down time. Ease of use promotes safety, user confidence, and lower skill and training requirements. MASS designs should be “user-oriented.”

Finally, some technologies will require support equipment of their own to keep the MASS running. For example, certain types of batteries require special rechargers that have to be carried along with them during deployment. This extra equipment would reduce the number of MASS units using this technology that could be transported during each sortie. Therefore, the technology would be less effective for MASS than another technology not requiring such support equipment.

User Needs - The comfort, safety, and convenience of AGE maintenance and operation was considered. The military environment, including the extremes of weather and the military flightline environment, both in peace time and in combat, was considered. Among other things, new AGE designs should be “human-centered.” This means considering the classical ergonomic criteria for access, ease of repair, and so forth, and also considering user needs explicitly in the selection of technologies for inclusion in new MASS designs.

Affordability - MASS designs should be consistent with engineering DoD requirements for affordability. In essence, this means that technologies were targeted for development with the aim of bringing down life cycle costs. MASS technologies were evaluated for affordability by estimating and comparing the acquisition and ownership costs of candidate technologies with current AGE designs.

Each technology in every engineering domain was evaluated by applying these criteria and using engineering judgments to rate the technology for that criteria. From these ratings, those technologies that best fit the criteria were selected and reported in this document.

3.0 Results

3.1 Summary of Procedures

This chapter describes the results of the work performed during Subtask 1. As previously noted, information was obtained on the state-of-the-art technologies through catalogs from vendors of such equipment and for future technologies through reports from universities, government, and private research agencies. The engineering domains selected as applicable to MASS were:

- Engines
- Electric Motors
- Air Conditioning Equipment
- Power Conversion Equipment
- Hydraulic Pumps
- Air Compressors
- Floodlights
- Nitrogen Supply Systems
- Batteries
- System Controls and Testing
- Engineering Materials.

Equipment vendors were the primary industrial source of data. Names of companies were obtained from reference sources such as the *Thomas Register* and the personal catalog collections of the technical experts. These experts contacted vendors who manufacture equipment in the domains of interest. They provided valuable information on currently available and near-term equipment.

The most useful literature search results were obtained from DTIC. Forty-two search terms encompassing the engineering domains of interest were searched individually and in multiple combinations to yield 3,017 citations. Of these, 77 reports were ordered for detailed review. These reports provide a good representation of the projects undertaken by the Air Force, Army, and Navy. The majority of the reports were from Air Force programs or Air Force sponsored contracts, mainly Wright Laboratory. These reports formed the core of the information gathered. Appendix A lists the references obtained and used during this subtask.

Review of *Partnerships: A Compendium of State and Federal Cooperative Technology Programs* led to on-line searches of DARPA, the National Science Foundation, the Office of Technology Transfer, and the National Institute of Standards and Technology's Advanced Technology Program. The few of the new equipment technologies identified during these searches were not mature enough for inclusion in a MASS demonstration unit by 1997.

The Compendex and the Applied Science and Technology Index were searched for relevant scientific and technical information. Searches were limited to articles written no later than 1988 to ensure that the journals provided the most current information available.

Once the technologies were identified and understood, they were evaluated. The evaluation criteria used were:

- Performance
- Deployability
- Environmental Impact
- Supportability
- User Needs
- Affordability.

These criteria were applied to each technology. A comparison was made by using the current capabilities of the AGE as a baseline. The baseline data were obtained from the COLORS Database Notebook, which describes the current AGE. When using these data, the

actual performance of current AGE was only a guide to the order of magnitude required for the performance of MASS. It is widely assumed that many current AGE systems are oversized, providing more capability than needed.

Each of the following chapter sections identifies the applicable technologies, describes and compares the technologies by applying the evaluation criteria, and summarizes their strengths and weaknesses. At the end of each section is a table listing the recommended technologies, that should be considered in the later tradeoffs to be conducted under Subtask 3.

3.2 Evaluation Results

3.2.1 Engine Technologies

Engines are defined as equipment for converting the chemical energy of a fuel into mechanical energy for driving other components. The technologies discussed in this section include the many ways of accomplishing this goal.

In current AGE, engines are used in many of the items. Table 1 lists the engines used in various types of equipment.

3.2.1.1 Applicable Technologies

Small Gas Turbine Engines. Turbine engines are commonly used in aircraft and in ground support equipment. Their high power, low maintenance, and fuel compatibility with the aircraft they service make turbine engines a strong candidate for inclusion in the MASS system.

Spark Ignition Engines. Although not usually as large or durable as diesel engines, spark ignition engines may still be applicable to MASS due to their low cost and light weight.

Diesel Engines. Diesel engines are durable, fuel efficient engines that are available in a wide range of sizes. Their all-purpose nature makes them a natural candidate to power a multi-function aircraft ground support system.

Stationary Internal Combustion Engines (IC). Stationary IC engines are different from other diesel and spark ignition engines mainly because they are larger, less integrated, and composed of more parts. Since the MASS application is not stationary, the benefits of using a stationary-type engine cannot be realized without introducing problems with weight and movement.

Table 2. Engines Used in AGE

Engine Type	AGE Type	AGE Designator
Gasoline	Air Compressor	MC-1A, MC-11, MC-2A
Diesel	Air Compressor	MC-1A, MC-2A, MC-6, MC-7
Diesel	Air Conditioner	A/M32C-17, A/M32C-18, A3D, ACE406-322, ACE406-329, ACE410-922, ACE410-927, ACE802-329, MA-1, MA-1A, MA-3D
Gasoline	Air Conditioner	A3, MA-3
Diesel	Heater	1H-1, H-1
Turbine	Start Cart	A/M32A-95, MA-1A, TMC85-1
Gasoline	Lighting	NF-2
Diesel	Lighting	NF-2D, TF-1
Turbine	Generator	A/M32A-85, A/M32A-60, A/M32A-60A, A/M32A-60B
Diesel	Generator	A/M32A-86, A/M32A-86A, A/M32A-86B/F, A/M32A-86D, A/M32A-86E
Gasoline	Hydraulic Test Stand	1620-100, MJ-2, MJ1, MJ1-1, MJ1-D5, MJ2A, TTU-228/E
Diesel	Hydraulic Test Stand	MJ-2A-1, MJ1-1, MJ2A, MJ2A-1, MJ3, TTU-228/E, TTU-228/E-1B

Alternative Fuels. Advances in engines burning alternative fuels or multiple fuels are under investigation with regard to each engine technology. Since the advantages and disadvantages of particular fuels vary according to the engine technology involved, alternative fuel issues will be discussed within the exposition of each candidate.

3.2.1.2 Description of Candidate Technologies

Gas Turbine Engines.

Operational Parameters. Gas turbine engines operate on the Brayton cycle, which consists of compressing air, heating a fuel and air mixture, and expanding the combustion products. Because the expanding gases are hotter, more work is produced during expansion than is required for compression. The net work output is the difference between the expansion work and the compression work. The efficiency of the Brayton cycle depends upon the pressure ratio, the turbine inlet temperature, and the parasitic losses. The efficiency of a gas turbine engine is proportional to its size. Small turbines use proportionally larger compressors and turbine blade tip clearances, relatively larger boundary layers in all flow passages, lower gas velocities, and a greater compromise of blade shapes to accommodate cooling passages while maintaining structural integrity.

Gas turbine engines can be operated in a simple or open cycle, or a regenerative or closed cycle. Simple cycles have higher exhaust temperatures, which can be an advantage if the heat energy is utilized, or a detriment as a safety hazard and an infrared source. Regenerators recycle the hot exhaust gas, thereby improving thermal efficiency.

Most technical advances in gas turbine technology have been initiated by users of large turbines, such as electric utilities and aircraft manufacturers. High temperature materials have been studied a great deal because the efficiency of the cycle rises with turbine inlet temperature.

Many types of ground support equipment are powered by turbine engines. Turbine-powered AGE has a high initial cost, high maintenance cost, and high fuel consumption when compared to other engine-powered AGE. Small turbine engines are more expensive (usually five to ten times the price), require more maintenance, and do not last as long as diesel engines. In some applications, such as a helicopter, a gas turbine engine will last two to three times longer than a piston engine due to the continuous high speed and high power level required. In fixed wing aircraft, the durability advantage of gas turbines is smaller because high power is used only for short durations at takeoff. Instead, it is the weight advantage that makes turbines more popular. In battle tank applications, volume is a more important design consideration than weight. Also, in tanks, low fuel consumption at low power (idle) is necessary. Turbine engines are only competitive in tanks if a regenerative heat exchanger is used to maintain high cycle temperatures and minimize fuel consumption at low power. Combustor cooling can be a problem in regenerative turbines because combustor inlet temperatures are high.

Over the life of a turbine, performance is degraded by the ingestion of particulates that can erode the precision-machined turbine blades. Because air intake volume is so high, even very elaborate filtering systems cannot prevent gradual degradation. Barrier filters and centrifugal separators are two methods of particulate ingestion prevention, both of which have drawbacks. Efficient barrier filters can create unacceptable inlet pressure losses that reduce engine output, while centrifugal separators are not efficient enough. Ingestion problems are much more severe in ground applications than in aircraft applications because dust concentrations are higher and exposure times are longer.

Both axial and centrifugal compressors can be used in turbine engines. Similarly, both axial and inward flow turbines can be manufactured. Axial designs are made of rotors and individual blades. They are more expensive and require more shaft length than radial designs, but they are also more efficient in large sizes. Radial compressors and turbine stages can be cast as a single part. Centrifugal compressors are often used with axial turbine blades. Axial compressors are more common in very large turbines used for electrical generation, while radial inward flow turbines are only used in very small, compact designs. The radial turbine is more rugged and less susceptible to erosion than the axial turbine.

Gas turbine applications are expanding as a result of their use in electrical co-generation and their successes in providing aircraft power. Past efficiency gains have spurred additional research on all aspects of gas turbine performance, promising that tomorrow's turbines will be more efficient and reliable than today's. Alternative fuels, emissions controls, and fault detection methods are all important innovations in gas turbine design. Among current research projects, carbon/carbon multidimensionally reinforced materials are being studied to raise the operating temperatures, and the efficiency, of gas turbine engines. Wright Laboratory is working with manufacturers of fiber composites to reduce these costs by 50 percent through Integrated Product Process Design (IPPD) and other Design-For-Manufacturing techniques.

Research is also proceeding on alternative fuels for use in gas turbines to replace the standard jet fuels currently used. Much of this work is targeted at large electric-generating turbines. Electric utilities would like to burn more coal-based fuel. In general, alternative fuels lead to performance penalties in ignition, lean blowoff, and combustion efficiency. Higher fuel viscosities and wider boiling point distributions adversely affect atomization and vaporization processes within gas turbine combustors. Analytical Fuel Effects Modeling, developed by Purdue University in 1980 for the U.S. Army Research Office, is an effort to help designers create more fuel-tolerant gas turbine combustors. This modeling effort determined that changes would be needed primarily in the injector or combustor areas of the turbine engine to accommodate a change in fuels or a range of fuels.

Evaluation Based on:

Performance. Turbine engines are the most powerful engine alternative, given their weight. Their efficiency depends on how much of the turbine exhaust heat is used. A regenerator can capture that heat making the cycle more efficient, but at the cost of driving up the turbine operating temperature. Some other components of a MASS system are also capable of using the turbine exhaust energy directly, thus maintaining high overall system efficiency. Such components include a liquid absorption, metal hydride, or air cycle cooling system, and an air

compressor. Turbines on the ground are particularly susceptible to damage due to ingestion of foreign objects into their compressors. Such objects could be battle related or products of an extreme environment. Although turbine engines are a mature technology, further advances in materials and small turbine design are possible.

Deployability. Turbine engines are the lightest engine candidate per unit power. They are also very compact, but require a larger fuel tank due to their low fuel efficiency.

Environmental Impacts. All engines are loud, but turbine engines are slightly louder than similarly sized reciprocating engines. Due to the high temperature of combustion in a turbine engine, NO_x emissions are higher than in other engines, even when burning the same fuel. Turbine engines can burn a variety of fuels, with varying degrees of performance. The resulting emissions are a property of the particular fuel chosen. Fuels that do not burn completely give off volatile organic compounds, while all fuels generate CO₂.

Supportability. Turbine engines require more maintenance than other types of engines, but because they are also used in aircraft, their maintenance requirements are already familiar to existing personnel. Turbine engines are not ideal for modular system designs. Instead, they lend themselves to integrated designs, in which redundant processes are eliminated, such as the compression of air in both a Brayton cycle cooling system and the turbine engine.

User Needs. Turbine engines are a familiar component of ground support maintenance. Maintenance on a MASS turbine engine could be more difficult than an aircraft engine since access could be more limited in order to make the system compact. In addition, noise is an ongoing safety issue regarding turbine engines.

Affordability. Development costs will be required to integrate a turbine engine into a complete MASS system. The basic technology is commercially available, but procurement costs remain high due to the materials used and the precision to which they must be manufactured to produce an efficient engine. Low operating and maintenance costs can offset some of the initial expense of this technology.

Spark Ignition Engines.

Operational Parameters. Spark ignition engines operate on the Otto cycle, which features constant volume combustion in the cylindrical space left by a reciprocating piston. Volatile liquids or gases can be used as fuel, although gasoline is by far the most common fuel used in automobile, airplane, marine, tractor, and stationary spark ignition engines. Spark ignition engines have an inherently limited cylinder size, since the flame front must propagate from the spark location to the most distant point in the cylinder before the cylinder moves appreciably.

Spark ignition engines can be either two-stroke or four-stroke, depending on the relative importance of cost, power density, fuel consumption, and load variance. Two-stroke engines are less expensive and generate more power per unit cylinder volume, while four-stroke engines have better fuel efficiency, easier power regulation, and lower exhaust emissions.

In aircraft propulsion applications, spark ignition engines are chosen over diesel engines because of their lower weight. Aircraft piston engines are generally four stroke designs and are available up to 300 to 400 HP. In applications of portable electric power generation, spark-ignition engines are generally used for outputs less than 20 kW, while diesels are used for larger power requirements.

Spark ignition engines also offer the option of air or water cooling. If the engine can be expected to be moving whenever it is running, such as in airplane engines, or if forced air flow can be provided, then lightweight, air-cooled engines can be used. If the engine must be able to idle without overheating, then a pumped water cooling system with a forced air radiator must be provided.

Research into alternative fuels for spark ignition engines has been pursued vigorously by the automobile industry, which is faced with ever-tightening environmental regulations. In automotive applications, the prime alternative fuels include liquid fuel substitutes such as ethanol, methanol, or reconstituted gasoline or diesel fuel. Reconstituting removes components

of the fuels which emerge in emissions. Gaseous fuels such as methane (natural gas), propane, and hydrogen are also potential alternatives.

Evaluation Based on:

Performance. Spark ignition engines usually are not used for systems requiring more than 20 kW of power, such as MASS. Air-cooled engines are less susceptible to battle damage than water-cooled engines, but overheating could be a problem in extremely hot environments. On the other hand, freezing coolant could cause problems in a water-cooled system at low temperatures. The spark ignition engine is a very mature technology due to its dominant presence in the automobile industry.

Deployability. Spark ignition engines are lighter than diesel engines and take up roughly the same volume. They are less fuel efficient, however, so fuel tank volume may be greater.

Environmental Impacts. Gasoline engines tend to have lower emissions than diesels. Alternate fuels which give even lower emissions are being developed. Designing an engine to run on multiple fuels leads to emission penalties. The use of alternate fuels which are less volatile than gasoline greatly increases emissions.

Supportability. In continuous operation, spark ignition engines are less durable than diesel engines. The use of several small modular engines is an option that could be implemented with spark ignition engines. This added redundancy would offset low durability, increase modularity, and allow the system to continue performing some tasks after being damaged. The use of gasoline instead of diesel or jet fuel is a drawback regarding the supportability of spark ignition engines.

User Needs. Air cooled designs are more accessible for repairs and adjustments. Advanced diagnostic tools exist for quickly evaluating performance. The more volatile fuel used in spark ignition engines can heighten the risk of explosion and fire.

Affordability. Procurement costs are the lowest of the candidate engine technologies. However, life-cycle costs may be higher due to low durability and high replacement rate.

Diesel Engines.

Operational Parameters. Diesel engines work without a spark plug by simply compressing an air/fuel mixture until it ignites and expands, pushing the piston away. When the cylinder is hot, auto-ignition occurs easily, but during start-up, ignition may need to be assisted by a glow plug. Diesel engines provide high power per volume of engine when fuel volume is included. For this reason they are preferred in ground combat vehicle applications where weight is a less important issue than mission duration. Diesel engines are more fuel efficient than gasoline engines, but have higher initial costs. Diesels also require less maintenance but are noisier and can be difficult to start.

Since pressure is increased uniformly in the cylinder of a diesel engine, ignition can occur throughout the cylinder at the same time, regardless of cylinder size. This enables diesel cylinders to be very large, if necessary. Diesel engines are available in sizes up to 40,000 kW (53,000 HP) for electric power generation and marine propulsion.

Supercharging is a common way to get more power from the same size diesel engine using the same fuel. It involves forcing hot air into the cylinder with the fuel before ignition. This creates a higher density fuel mixture than in a naturally aspirated engine and increases the stresses placed on the engine parts.

Several types of alternative fuels for diesel engines are being studied, mainly to reduce reliance on foreign oil supply. Environmental improvements are a secondary goal for diesel substitutions. One possible alternative to diesel fuel is alcohol fuel, such as ethanol or methanol. One common difficulty with alcohols is their low cetane number, which indicates how easily they ignite. This is critical in diesel engines, where no spark is provided. Ignitability can be improved with additives, however. There are three basic alternative fuel technologies that involve alcohol fuels: cetane-improved alcohol fuel, alcohol-oil fuel blends, and alcohol fumigation.

Alcohols have a lower heating value than diesel fuels or gasoline, and thus require a higher fuel flow rate. Performance measures such as the mean effective pressure and specific

fuel consumption are comparable for ethanol with ignition improvers and diesel fuel. Emissions from engines with alcohols have less hydrocarbons and less black smoke. The NO_x output of a diesel engine using ethanol is worse than one using diesel fuel at low speeds (below 45 percent capacity), but better than diesel at higher engine speeds. Burning alcohols generally leads to larger releases of formaldehyde than gasoline or diesel fuels. Releases of unburned alcohols in exhaust or evaporative emissions are also an environmental concern. Alcohol fumigation involves burning both diesel fuel and alcohol, where the diesel fuel acts as a pilot light for the alcohol combustion. Up to 30 percent of the energy requirement can be met by ethanol using this procedure. Ignition delay time increases as the fraction of alcohol is increased. When the delay is large, engine knock results. Although particulate levels generally decrease with alcohol use, limited testing has indicated that the biological activity of the particulate may be greater. This could open up new health questions. In general, the alcohol fuels performed better at high speeds but worse at low speeds compared to the baseline diesel engine.

Another type of alternate fuel is coal-based fuel. Burning coal-oil slurries causes increased wear at all speeds. Combustion performance is not as good as baseline diesel fuel, and special problems with injection and pumping are introduced. Liquified coal-based fuel is the most feasible of the coal fuels. However, it has slightly higher emissions and was tested only at very low engine speeds (120 rpm).

Vegetable oils also have been demonstrated as diesel replacements alone or in mixtures with diesel fuels. Both peanut and soybean oil are capable of performance within 10% of baseline diesel with no engine modification. Cold start up may need to be diesel or ether assisted, however. A blend of 20 percent soy oil and 80 percent diesel fuel has been tested in buses with good results. Also, mixtures of soy oil and ethanol have been attempted; however, start-up must be assisted and the low flash point is a problem.

Evaluation Based on:

Performance. Diesel engines are compact, efficient power producers. With proper use, they last longer than other types of engines. Since ignition requires high temperatures as well as pressures, diesel engines can be difficult to start in cold weather. They are the most fuel efficient engine technology candidate, and their stout construction and durability make them somewhat less susceptible to battle damage. Diesel engines are a very mature technology, whose only significant avenue of ongoing research is in alternative fuels.

Deployability. Although diesel engines are compact, they are the heaviest of the candidate engine designs.

Environmental Impacts. Emissions from diesel engines are higher than those of either spark ignition engines or gas turbine engines. Alternative fuels generally make emissions worse, or at best, maintain existing levels.

Supportability. Maintenance of diesel engines is more frequent than for other types of engines. However, as with gasoline engines, diesel maintenance tasks are common and probably familiar to technicians. Diesel engines and their parts may be common with other ground support equipment. Diesel engines also create a high level of vibration when they operate, which could affect the operation of other MASS subsystems. Both the functionality and rate of maintenance of other components could be negatively influenced by engine vibration.

User Needs. Diesel engines are noisy when they operate, and are hardest to operate in cold weather, when it is least convenient to service them.

Affordability. Procurement costs are competitive with other technologies, while operating costs could be higher because of higher maintenance requirements. Because of their high durability, life-cycle costs may be lower than those of other engine technologies.

3.2.1.3 Comparison and Summary

As shown in Table 3, turbine engines offer many benefits when combined with other MASS components in an integrated system design. Conversely, spark ignition engines are simple, small, and could be implemented in groups of two or three engines for increased redundancy and modularity. But, their lack of fuel compatibility will be a drawback. Diesel engines are the traditional workhorses of large, ground-based equipment like MASS, because of their power, fuel efficiency, and durability.

Table 3. Engine Evaluation Summary

Engine Technologies	Advantages/Strengths	Disadvantages/Weaknesses
Gas Turbine Engine	High power to weight ratio Clean emissions Low vibration	High procurement costs High fuel consumption Noisy operation
Spark Ignition Engine	Low procurement cost Light weight	Low durability Limited size
Diesel Engine (Compression Ignition)	Low fuel consumption High power to volume ratio High durability	Difficult cold starting Noisy operation

3.2.2 Motors

Electric motors are used to convert electrical power into mechanical motion. For MASS, they could be the drivers for all of the other functions such as air conditioning or hydraulic power. The current program on Electro Multifunction Ground Equipment (EMAGE) is reviewing the possibility of using electric motors exclusively for MASS.

Motors are used throughout the current AGE for many different purposes. Table 4 lists the AGE using electric motors as the primary source of power.

Table 4. Motors Used in AGE

AGE Type	AGE Designation
Air Compressor	MC-11
Air Conditioner	A/M32C-39, A/M32C-4, A/M32C-5, ACE406-392, ACE802-392, ACE802-392S, MA-3M, MA-8
Heater	H DU-13/M
Hydraulic Test Stand	AHT55B, AHT6, AHT6A, AM27-T2A, AM27T2, MH-2, MK1, MK1 (D6), MK1A, MK3, MK3A, MK3A-1, MK3A-B1, MK3A3

3.2.2.1 Applicable Technologies

Brush DC. The brush DC motor is the most commonly used motor technology for controls applications. It is discussed in detail in the following section.

Polyphase Synchronous AC. Polyphase synchronous AC motors are not appropriate for use in a MASS system because they have no starting torque. Some method must be implemented to bring these motors up to synchronous speed before they can be used effectively.

Polyphase Induction AC. Polyphase induction is the most commonly used motor technology for large-scale energy conversion under essentially steady-state conditions. It is discussed in detail in the following section.

Single Phase AC. Single phase AC motors are typically used for small power applications and where three phase power is not available. It is discussed in the following section.

Brushless DC. A brushless DC motor is typically used in high performance control systems. It is discussed in detail in the following section.

Stepper Motors. Stepper motors are not appropriate for use in a MASS system because of their low power capability and microprocessor control requirement.

3.2.2.2 Description of Candidate Technologies

Brush DC.

Operational Parameters. Brush DC motors convert direct current (DC) electrical energy into mechanical energy. Each motor is composed of a stationary part, called the stator, and a rotating part, called the rotor. The rotor is mounted on a stiff rod, called the shaft. The shaft is supported by bearings so that the rotor is free to turn. The shaft extends through one or both of the bearings to provide a means to connect the motor to the mechanical system.

DC motors are designed to produce a torque proportional to the DC current applied. The direct-drive DC torque motor is probably the most linear kind of servo actuator. The common motor parameters, stall torque and no load speed, are almost perfectly linear functions of applied voltage. Distinctive to AC servo-motors, its family of speed-torque characteristics is a parallel set of straight lines that do not exhibit the loss in damping at low control voltages. Because of this, DC motors can be easily controlled in servo-mechanical systems. The reason for the DC motor's linearity is its brushes and commutator. These brushes and commutator produce a stationary rotor magnetic pole while the rotor is rotating. Unfortunately, because of arcing on the

surface between the brushes and commutator, the speed and current of the brush DC motor are limited. In addition, the complexity of the brush DC motor results in higher construction cost and periodic maintenance.

The main field of a DC motor is produced by either passing a DC exciting current through the main field winding or by using a permanent magnet. Those motors that utilize a DC exciting current are known as wound-field DC motors, and can consist of four types: separately excited, shunt, series, or compound DC motors.

Separately excited DC motors have the armature (rotor) and field (stator) winding current supplied from two separate sources permitting speed control below base speed by supplying the armature with a variable voltage. Speeds above base speed are obtained by reducing the field.

Shunt DC motors have the armature circuit in parallel with the field circuit to give almost constant speed output over its operating load range. Series DC motors have the armature and field winding connected in series to produce a speed that is inversely proportional to the torque. A combination of the two motors is the compound DC motor. Compound DC motors have the armature in parallel with a shunt field winding and a series field winding connected in series to produce an operating characteristic that is in between that of the shunt and series motors.

A permanent magnet DC motor has the field winding replaced with a permanent magnet. Therefore, the stator magnetic flux remains essentially constant at all levels of armature current, and the speed-torque curve of the permanent magnet motor is linear over an extended range from the wound-field type. The motor drive circuitry is also simplified.

Evaluation Based on:

Performance. Brush DC motors are capable of meeting the requirements for the MASS program under certain conditions. The brush DC motors require a DC power to operate. In addition, these motors will have to be hermetically sealed to prevent any arcing on the commutator from igniting any hazardous fumes.

Deployability. Due to the brushes and commutator in the motor, and the need to hermetically seal, this motor will tend to be larger than other technologies.

Environmental Impact. No hazardous materials are expected to be needed for the brush DC motors.

Supportability. For high power applications, periodic maintenance on the motor's brushes and commutator will be required.

User Needs. Not applicable.

Affordability. Brush DC motors are a developed technology. However, the need for brushes and commutators that can handle high power and a hermetically sealed case will increase the cost to a moderate level.

Polyphase Induction AC.

Operational Parameters. AC motors depend on a rotating magnetic field between the rotor and stator. They are designed to produce a torque that is roughly proportional to the AC signal applied. The advantage of the AC motor over the DC motor is that the high current brushes and commutators are not present. This allows for higher speed and torque outputs from the AC motor. The disadvantage of the AC motor is that it requires a more complex drive circuitry when used in servo control systems. As a result, AC motors are preferred for high speed, constant velocity applications that can be powered directly from an AC supply.

The polyphase induction motor is the simplest and most widely used AC motor. Their construction consists of two or more (typically three) armature windings on the stator and a field winding on the rotor. The rotor windings are short circuited. This results in the rotor current being generated from induction, rather than conduction. Induction motors also are referred to as asynchronous motors because their operating speed is slightly less than the synchronous speed.

There are two main types of induction motors: squirrel cage and wound rotor. The squirrel cage induction motor is the most widely used motor of any type because of its rugged

simplicity and low cost. The wound rotor motor provides greater flexibility than the squirrel cage motor because it has an adjustable speed and high starting torque with low starting current.

The polyphase induction AC motors are rugged, relatively inexpensive, and require very little maintenance. However, the disadvantages of induction motors are that the speed is not easily controlled, the starting current is high, and the power factor is low when the motor is lightly loaded.

Polyphase induction motors are available from a few tenths to about 10,000 HP.

Evaluation Based on:

Performance. Polyphase induction motors are capable of meeting the requirements for the MASS program. These motors are designed for high power applications that supply power from a three-phase AC power system.

Deployability. The polyphase induction motor will provide a compact design for the MASS program.

Environmental Impact. No hazardous materials are expected to be needed for the polyphase induction AC motor.

Supportability. No significant maintenance should be required for the induction motor.

User Needs. Not applicable.

Affordability. The polyphase induction AC motor is a mature technology. Development and procurement costs will be both low and stable.

Single Phase AC.

Operational Parameters. Single phase AC motors are typically used for small power applications and where three phase power is not available. The difficulty with single phase motors is their requirement to produce a rotating magnetic field. Several schemes have been developed to achieve this requirement. Each results in a motor with specific characteristics, that

are suitable to a certain range of uses. Single phase AC motors may be classified as three types: commutator, induction, or synchronous. The following single phase AC motors represent the most important of these motor types.

The universal motor is a DC motor adaptable to AC. The motor is designed so that when the line current reverses direction, the field and armature currents reverse simultaneously. In addition, the motor is designed so that the core loss with alternating flux is relatively low. These motors operate successfully between any frequency from DC to its designed limit. The top design frequency for universal motors is typically 60 Hz. For comparison, the turbine generator is 400 Hz.

A single-phase induction motor is similar to a polyphase squirrel cage induction motor with only one input phase connected. This results in a pulsating stationary field that alternates in polarity. A stationary rotor in this field would have no starting torque. However, once the motor is started, currents are induced in the rotor, and this causes a rotor magnetic field to be produced. The torque developed by a single phase induction motor is not constant but pulsates even at no load. Single phase induction motors are named in accordance with the type of starting method that is used. Split-phase, capacitor-start, and shaded-pole motors are single phase induction motors that take their names from the starting method.

Evaluation Based on:

Performance. Single phase motors are capable of meeting moderate power applications for the MASS program. Most of these motors are typically less than 1 HP, with a few available up to 10 HP.

Deployability. The single phase motor will provide a compact design for the MASS program.

Environmental Impact. No hazardous materials are expected to be needed for the single phase AC motor.

Supportability. No significant maintenance should be required for the single phase AC motor.

User Needs. Not applicable.

Affordability. The single phase AC motor is a mature technology. Development and procurement costs will be both low and stable.

Brushless DC.

Operational Parameters. Brushless DC motors are permanent magnet synchronous motors that have an inside-out version of a permanent magnet DC motor. Because the armature currents are supplied to the stator, as opposed to the rotor, there is no need to have brushes. Instead, the commutation function is performed by electronic means. This requires a complex motor drive circuit and the addition of a position sensor on the motor. Therefore, any evaluation of a brushless motor must also include its drive circuitry.

Brushless motors and amplifiers can be categorized by the current waveform. Trapezoidal drives are mainly used for low performance servos where extremely low speed operation is not considered. Sinusoidal drives offer high performance due to sophisticated control and low torque ripple.

Brushless motors offer very low inertia and maintenance-free construction at the price of higher system cost.

Evaluation Based on:

Performance. Brushless DC motors are capable of meeting the requirements for the MASS program for applications below 20 KVA. Above that power level, other motor technologies are more appropriate. These motors are typically used in high performance control systems.

Deployability. Brushless DC motors have a very small size envelope for the power density. However, additional space must be allocated to the drive circuitry.

Environmental Impact. No hazardous materials are expected to be needed for the brushless DC motors.

Supportability. No significant maintenance should be required for the brushless DC motor.

User Needs. Not applicable.

Affordability. The brushless DC is the most expensive of the motor technologies being evaluated. These motors require rare earth magnets and an integrated position sensor. In addition, these motors require a complex drive amplifier that increases the overall system cost.

3.2.2.3 Comparison and Summary

The exact motor for the MASS program awaits specific requirements for the system. Each application in the MASS unit will dictate which motor should be used. The AC induction motor appears to be the best candidate for the high power MASS applications (see Table 5).

Table 5. Electric Motor Evaluation Summary

Motor Technologies	Advantages/Strengths	Disadvantages/Weaknesses
Brush DC	Easily powered from DC power bus Linear speed-torque curve	Limited speed-torque capability Arcing on brushes and commutator Periodic maintenance required
Polyphase Induction AC	Easily powered from three phase AC power bus Rugged Relatively inexpensive Requires little maintenance	Exact motor speed is not easily controlled Starting current is high Power factor is low when the motor is lightly loaded
Single Phase AC	Powered from single phase AC power bus	Limited power rating
Brushless DC	Small motor size for power density Requires little maintenance	Expensive Requires complex motor amplifier

3.2.3 Air Conditioning Technologies

Cool air is needed to prevent the electronic equipment from overheating during maintenance. Cool air is also used for cabin/crew comfort. Two of the many air conditioning technologies available are used in current AGE. One of the technologies is vapor compression, which requires a refrigerant such as Freon; and the other air cycle, which requires a high volume of pressurized air (usually provided by a turbine engine). For example, the A/M32C-10, -10A, -10B, -10C, and -10D are air cycle systems and require air from the A/M32A-60 turbo-generator to operate. Others, such as the A/M32C-4, -5, -17, -18, and -39, use vapor compression technology.

3.2.3.1 Applicable Technologies

Vapor Compression. Vapor compression refrigeration is the most commonly used cooling technology in the world. It is considered to be a good candidate for consideration in a MASS system due to its technical maturity and wide range of applications.

Stirling Cycle. Stirling cycle refrigeration was considered as a MASS option and ruled out due to its low efficiency and need of bulky heat exchangers.

Brayton Cycle (Air Cycle). Air cycle cooling is used in aircraft cooling applications due to its light weight and compact size. It is considered to be a good candidate for consideration in a MASS system.

Liquid Absorption. Liquid absorption technology allows a cooling system to be driven primarily by a heat source, instead of an electrical source. Since waste heat may be available on a MASS unit, this cooling method is considered to be a good candidate technology that may be particularly efficient as part of a multifunction support system.

Solid Absorption (Metal Hydride). Solid absorption is a new, developing technology with several unique advantages. It is worthy of consideration as a MASS system component.

Ejector Cooling. Ejector cooling systems are not appropriate for use in a MASS system due to their insufficient cooling capacity.

Thermoelectric. Thermoelectric refrigeration systems are not appropriate for use in a MASS system. They have low efficiency and insufficient cooling capacity.

Thermoacoustic. Thermoacoustic refrigeration is a new technology, judged to be unsuitable for MASS since it is unproven at high capacities.

Sonic Compressor. The sonic compressor concept is a modification of the vapor compression cycle. It is currently unproven, and provides minimal performance benefits over conventional vapor compressors.

Endothermic Reaction. Endothermic reactions can provide chemical cooling for a short time, but they are poorly suited for sustained operation at high capacity, such as that required in a MASS unit.

Vortex Tube. Vortex tube refrigeration systems are not appropriate for use in a MASS system because of their insufficient cooling capacity.

Liquid Compression (Malone Cycle). Malone cycle refrigeration is commercially unproven, but it is a candidate technology for MASS owing to its potential for producing compact designs with high cooling capacities.

Evaporative Cooling. Evaporative cooling technology was found to be unsuitable for MASS, primarily because its system performance capacity is greatly dependent on the surrounding temperature and humidity. Evaporative cooling takes advantage of the heat-absorbing capacity of a liquid such as water when it evaporates into a gas.

3.2.3.2 Description of Candidate Technologies

Vapor Compression.

Operational Parameters. Vapor compression uses the Rankine cycle refrigeration principle. It is widely used in home refrigerators and air conditioners. A refrigerant, such as Freon, passes through an evaporator where heat is absorbed and the refrigerant vaporizes. The refrigerant gas then enters a compressor where the gas temperature and pressure increase. The gas then passes through a condenser where it condenses into a liquid and rejects heat to the environment. The refrigerant passes through an expansion valve to reduce the temperature and pressure before it enters the evaporator again. Mechanical input power is needed to drive the compressor. The system efficiency is described as the Coefficient of Performance (COP) and is typically two to three for vapor compression systems. This means that, due to the characteristics of the system, the energy input to the system is one-half to one-third the energy removed as heat.

To achieve very low temperature air relative to ambient air, two vapor compression cycles can be cascaded so that the evaporator of one cycle cools the condenser of the other cycle. Two different refrigerants are sometimes used, based on the operating temperatures of the two cascaded cycles.

The vapor compression cycle has many inherent advantages. The heat exchangers used in a vapor compression system tend to be compact because of the high rate of heat transfer in condensation and evaporation. Vapor compression is the most common technology for commercial refrigeration. Because of this, a large number of different refrigerants are available.

The use of condensation and evaporation heat transfer provides efficient compact heat exchangers. However, it also limits the useful temperature range of a given system, so that different working fluids are needed for different temperature ranges. Another drawback to the vapor compression cycle is that many of the refrigerants that work best at desirable temperatures contain ozone-depleting chlorofluorocarbons (CFCs).

For vapor compression air conditioning systems with large cooling capacities, it is often more convenient to use an intermediate liquid, or brine, than to cool the air directly. The higher specific heat and density of water, compared to air, prevent the size of the refrigeration system from getting extremely large. Water to air heat exchangers can then be placed wherever the air needs to be cooled, or the cold water, or brine, can be used to directly cool a piece of equipment.

Vapor compression technology is the standard for the refrigeration industry. Cooling capacities for air conditioners range from 1/12 ton to 75 ton (1 ton of refrigeration is equal to 12,000 Btu/hr cooling). Liquid chillers using vapor compression technology range in capacity from 1/4 ton to 115 ton. The A/M32C-10 is capable of providing up to 15 tons of refrigeration.

Vapor compression refrigeration has been used for 160 years. Much of the emphasis on technology innovation has been on development of alternative refrigerants. Because of ozone depletion, Freon and other CFC compounds are barred from production.

Evaluation Based on:

Performance. Vapor compression air conditioning technology is commercially available in large capacity units capable of meeting MASS requirements for cooling load. Cooling capacity and efficiency drop quickly when operating conditions deviate from design values. Compressors can be hermetically sealed to protect them from environmental hazards. However,

both the evaporator and condenser must draw air across their surfaces, which could lead to fouling and reduced efficiency. Fans and blowers are also susceptible to damage.

Deployability. In order to meet cooling load performance requirements, a vapor compression unit may be quite large and heavy, up to 1200 pounds and 150 cubic feet. This is very similar to the A/M32C-10, but does not include wheels and other components necessary for mobility.

Environmental Impacts. Many of the refrigerants with the best performance capabilities contain CFCs or hydrochlorofluorocarbons (HCFCs), which are thought to be harmful to the ozone layer. Most maintenance activities performed on vapor compression refrigeration systems require the refrigerant to be purged and later replenished. It is possible to contain the gaseous refrigerant and reuse it when the repairs are complete. However, this requires additional maintenance equipment and additional time and skill from the responsible technician. New refrigerants, including hydrofluorocarbons (HFCs), are currently being developed to preclude ozone layer damage, with a minimum performance penalty.

Supportability. Vapor compression systems have several moving parts including two fans or blowers, and a compressor, usually of the positive displacement variety. These components are very common, and therefore easy to stock. All components in the vapor compression system can be electrically powered, which increases the potential for system modularity. Because of the need for two streams of external air to flow over the two heat exchangers, one of which must then be ejected to the surroundings, there are some limits on system configuration regarding placement of the cooling system in the overall MASS unit.

User Needs. Providing sufficient access for maintenance operations will require some concessions in system size. Troubleshooting is simple since the symptoms of component failure are obvious (i.e., fan stops turning), except for loss of coolant, which can be gradual and invisible. The common, reliable, low-tech components that compose a vapor compression refrigeration system, as well as the chemically stable refrigerant, result in a high level of safety.

Affordability. Because of the maturity of this cooling technology, development costs will be very low and procurement costs will be both low and stable. A 15-ton vapor compression unit can be purchased off the shelf for \$12,000.

Brayton Cycle (Air Cycle).

Operational Parameters. In Brayton cycle cooling, also called air cycle cooling, air is compressed, cooled in a heat exchanger to reject heat, expanded in a turbine, and passed through another heat exchanger to absorb heat. Mechanical input power is required for the compression. This is the reverse of the cycle used to extract power in a gas turbine engine. Modifications to the basic cycle are suitable for specific applications such as very low temperature cooling and aircraft cooling.

To achieve very low temperatures, a regenerative heat exchanger can be added to the Brayton cycle. This allows the high pressure coolant to give up heat internally to the low pressure coolant after it has given up as much as it can to the external surroundings. This is commonly done in the liquefaction of gases where the coolant must achieve a temperature far below ambient.

A different modification to the Brayton refrigeration cycle is often used in aircraft cooling systems. In this case, an open cycle system is used. Inlet air is compressed, cooled by the ambient surroundings, and expanded through a turbine, where it does work and cools itself. Then, instead of absorbing heat through a heat exchanger, the cold air is simply released into the cabin of the aircraft to provide cooling. Open cycle operation is possible because air is the refrigerant. By eliminating one heat exchanger, and by using the turbine expansion work to assist the air compressor, a significant weight advantage is achieved over other cooling systems.

The Brayton cycle is not thermodynamically efficient. It has a low COP relative to the vapor compression cycle at the same temperatures, because of the large temperature variation in the heat addition and heat rejection stages.

Evaluation Based on:

Performance. Although it is inefficient, air cycle cooling can supply the large cooling loads required for MASS, provided there is a sufficient supply of compressed air available . The load is easily adjusted by changing the temperature of the outlet air. Since large amounts of air are required to operate this system, it is susceptible to damage due to ingestion of foreign objects. The Brayton cycle works best when paired with a turbine engine power source, since the air compression can be carried out by the shaft work of the turbine, reducing the size of the cooling system hardware.

Deployability. The open Brayton cycle will provide the most compact design of the candidate cooling technologies if linked with a turbine engine.

Environmental Impacts. Since air is the coolant, no hazardous chemicals are present that could potentially leak out. Noise is a significant concern, because the best way to generate the required volume of compressed air is with a turbine engine. The noise problem is not directly a product of the air cycle cooling, but of the turbine engine associated with it.

Supportability. When operated in an open, once-through cycle, there are very few parts, and subsequently few components will break or malfunction. The tradeoff required by the air cycle to be both simple and compact is a distinct lack of modularity. The air cycle system takes advantage of the presence of a turbine in the prime mover to dramatically reduce its own size.

User Needs. The variable temperature output available from an air cycle system makes it responsive to the needs of users in any weather condition. All of the moving parts needed in an air cycle system are also components of the turbine engine power system and are more properly discussed with regard to turbine engine maintenance.

Affordability. Air cycling is not new and will not require development costs. Because of their close relationship with, and dependence on, turbine engine components, procurement and other costs of air cycle systems are inextricably linked to costs of turbine engines, which are quite high.

Liquid Absorption.

Operational Parameters. Liquid absorption is different from vapor compression in that the compressor is replaced by an absorber and generator, which use heat to increase the temperature and pressure of the working fluid. The absorber contains a liquid absorbent that absorbs the gas from the evaporator. The absorbent with the working fluid is pumped to the generator and heated to evaporate the working fluid, which then flows into the condenser. The absorbent circulates back to the absorber. Parasitic power is required to operate the solution pump; however, the work required to increase the pressure of a liquid solution is much smaller than that required to compress a vapor.

A liquid absorption refrigeration cycle works by absorbing low pressure refrigerant vapor (such as ammonia) into a less volatile liquid (such as water). The liquid mixture is pumped to the condenser, and the refrigerant is separated from the mixture by the addition of heat, which boils off the more volatile component. Once the refrigerant is isolated, it travels through the condenser, expansion valve, and evaporator, as in a vapor compression cycle. To make the cycle more efficient, three levels of heat regeneration are possible: liquid heat exchange (LHE), absorber heat exchange (AHE), and generator absorber heat exchange (GAX). In LHE recuperation, the weak solution leaving the generator gives up heat to the rich solution leaving the absorber. In AHE recuperation, the latent heat of absorption is converted to sensible heat in the rich solution through a heat exchanger inside of the absorber. In GAX recuperation, the latent heat of absorption is transferred to the generator where it provides the heat needed to evaporate refrigerant vapor. The GAX cycle provides the highest efficiency possible in a single-stage cycle.

Since heat is the primary input, refrigerant loops can be linked in series with a heat exchanger such that the heat rejected from a very high pressure loop is used to drive a lower pressure loop which actually performs the cooling duty. This is called a double-effect cycle and is more thermodynamically efficient than a normal, single-effect cycle. Triple-effect cycles are also possible. Most of the energy that powers the cycle comes from heat input, not compressor

work. This can be an advantage if heat is more readily available, or cheaper, than electricity. Another inherent advantage of a liquid absorption cycle is that pumping the two-component liquid mixture up to high pressure takes less energy than compressing a vapor to the same pressure.

More heat exchangers are needed to make the cycle more efficient than a vapor compression cycle. Double-effect and triple-effect cycles require many more heat exchangers, while the GAX cycle needs only a few more.

Absorption systems are competitive with vapor compression systems for capacities above about five tons. For very small systems, the complexity of the cycle makes this technology prohibitively expensive.

This technology is being pursued forcefully by the natural gas industry in an effort to replace many residential electric heat pumps with gas-fired absorption systems. Smaller, more efficient heat exchangers should soon allow this technology to be economically competitive with electric-powered vapor compression systems and to expand its commercial presence.

Evaluation Based on:

Performance. Absorption refrigeration systems are primarily noted for their use of heat energy over electrical compressor work. In most applications, this heat is provided directly by burning fuel. However, in a MASS application, indirect or waste heat may be sufficient to drive an absorption cycle, thus reducing the power demand of the air conditioning unit. Since absorption systems rely on a condensing and evaporating refrigerant, they operate most efficiently in a relatively narrow temperature range specific to the refrigerant chosen. Absorption cooling is a mature technology used today in many specialized applications. Research is continuing in efforts to expand the applicability of absorption systems and possibly replace many vapor compression systems that rely on environmentally damaging CFCs.

Deployability. Because they require several heat exchangers, absorption systems tend to be larger and heavier than other systems. Efforts are underway to make absorption systems competitive in the residential heat pump market. Enhanced heat transfer surfaces and clever designs can still reduce the weight and volume of absorption cycle hardware.

Environmental Impacts. Absorption refrigeration systems conform to all environmental regulations and are considered a potential replacement for CFC-based vapor compression chillers.

Supportability. Absorption systems are more complicated and have more parts than comparable cooling units. Although electronic controls should make operation easy, maintenance tasks could require more knowledge. Modularity would drastically reduce the efficiency of an absorption system, which derives a large benefit from its union with a waste heat source.

User Needs. Ammonia is a strong irritant that brings a degree of danger to users if it escapes from the system. Lithium-bromide systems have been operated safely in many applications and have the additional advantage of being non-gaseous at atmospheric pressure.

Affordability. To take advantage of the waste heat available from a turbine engine, or other prime mover, development dollars would be needed to create a customized absorption system design. There is no question that such a design could be conceived, so the risk is low, but a modest development effort would be needed to make an absorption system efficient in a MASS application. Procurement costs are generally higher for absorption systems than for vapor compression systems because of their need for heat exchangers.

Solid Absorption.

Operational Parameters. Like liquid absorption, solid absorption utilizes heat energy, plus some parasitic electrical energy, to drive a cooling cycle. At the chemical level, solid absorption is very similar to liquid absorption. However, unlike a liquid absorption cooling

system, the solid cannot be pumped from one heat exchanger to another. Instead, the air streams for heat addition and removal must be periodically inverted to make a practical cooling system.

Metal hydride absorption systems have been developed that use two dissimilar metal alloys which react with hydrogen gas, but at different temperatures and pressures. The alloy that reacts at higher temperatures absorbs waste heat at a high temperature, which releases the hydrogen gas from the metal. The hydrogen gas is then sent to the lower temperature alloy, which absorbs the hydrogen and gives off heat until all the hydrogen is absorbed. The low temperature alloy then provides the cooling load by absorbing heat from the already cool air. As it absorbs heat, it gives up its hydrogen to the high temperature alloy so that the cycle can repeat.

This promising new technology uses much less electricity than equivalent vapor compression systems. It receives much of its power from heat, so the net effect of a metal hydride system is to consume waste heat, instead of generating it. Other advantages include the low number of moving parts and quiet operation, since it requires no compressor, just fans.

Metal hydride cooling systems will share one disadvantage with vapor compression systems. Different alloys are needed to operate at different temperatures. As with any design that uses hydrogen as a working fluid, there is the risk of explosion. However, in a metal hydride system, much of the hydrogen inventory is bound in the metal lattice, so the risk of explosion is very small.

A 9000 Btu/hr metal hydride system was designed by Ergenics to replace an equivalent vapor compression system currently used by the Army. This system was predicted to be 17 percent lighter than the vapor compression system and to occupy roughly the same amount of space. Because of its use of waste heat, this system required 87 percent less electricity than the current vapor compression system.

Although it is a relatively new technology, early prototypes of metal hydride systems are already comparable in size and performance to existing systems.

Evaluation Based on:

Performance. Very large capacity systems have not yet been developed using metal hydrides and could pose problems, despite the technology's apparent weight advantage over vapor compression systems. Like vapor compression systems, metal hydride systems must be designed for operation over a specific temperature range. This range can be wide, but a wider range produces a penalty in cooling capacity. The presence of hydrogen as the working fluid makes the system susceptible to battle damage. Metal hydride absorption cooling is a very new technology which has the potential to make further advances in efficiency, supportability, and cost.

Deployability. In tests to supplant Army vapor compression air conditioners, a metal hydride system was designed that was 17 percent lighter with the same volume as the vapor compression system. Volume reductions may not be proportional within higher capacity units.

Environmental Impacts. Many alloys are capable of working as a lattice of a metal hydride system. Some of these metals could be hazardous. However, since they are designed to operate in a solid phase, and to be sealed inside the same vessels that contain the hydrogen gas, no adverse environmental impact is expected. Safe materials can be selected in the design process, and many new alloys certainly will be developed as this technology matures.

Supportability. The self-contained and heat-driven characteristics of the metal hydride system are expected to make it very reliable. Fans, directional dampers, and controls appear to be the components most likely to need replacement or repair.

User Needs. It has yet to be established how easy metal hydride systems will be to operate. They are expected to run quietly since no compressor is used.

Affordability. Development costs will be significant for this technology. Procurement costs may be high as well, because of the use of large quantities of special alloys. Operating costs will depend on reliability and maintainability issues which are, as yet, unresolved.

Liquid Compression (Malone Cycle).

Operational Parameters. A Malone refrigeration system takes advantage of the cooling effect of a liquid that expands from a high pressure state to a lower pressure state, but not so low as to cause the liquid to flash into vapor. Despite the common assumption that liquids are incompressible, some liquids can be compressed significantly, near their critical point, and can cool substantially when expanded. Motor driven piston pumps can generate the high pressures needed for the cycle. High specific heat of liquids, combined with high densities, allow for very compact designs and high cooling capacities. Liquid carbon dioxide and dilute mixtures of alcohols in carbon dioxide provide safe, efficient, and inexpensive working fluids. Higher efficiency than conventional refrigeration equipment is expected, although current experimental units have not been optimized for efficiency.

The components of a Malone cycle system must be heavy to withstand the high internal pressures. Tight dimensional tolerances, also needed because of high pressures, may lead to high manufacturing costs. Since the working fluid must operate in a range near its critical point, different liquids can be used to achieve optimal performance in different environments. The useful ranges of working liquids are typically wider than those of phase-changing refrigerants, making the Malone cycle less dependent on ambient conditions than other systems. For example, propylene has a working range of 0 to 197 F° (-18 to 92 C°), and an experimental demonstration unit has been tested at Los Alamos National Lab using this material. Liquid carbon dioxide, with a critical temperature of 88 F°, is a refrigerant option for lower temperature applications.

Malone refrigeration is a new technology; proof of principle was demonstrated just 10 years ago. Its time to commercialization will depend on continued funding for prototype construction. In addition to Los Alamos, the David Taylor Research Center at Annapolis is

working on this technology. Malone cycle systems are expected to be most competitive in large capacity industrial and residential applications.

Evaluation Based on:

Performance. Although efficiency has not yet been demonstrated, many losses have been identified in current experimental units which can easily be eliminated in production models. Cooling capacity is expected to be a strength of the Malone cycle due to the high heat capacities of the liquid refrigerants available. Since the working fluids in a Malone cycle refrigerator are effective from 70 to 100 percent of their critical temperature, Malone systems should be capable of operating over a reasonably wide range of ambient conditions. High strength components may increase this system's susceptibility to battle damage over other refrigeration equipment. As a new technology, room for technical improvement and innovation still exists.

Deployability. High energy density will lead to compact designs using this technology. Weight may be high in order to provide sufficient pressure containment.

Environmental Impacts. No hazardous materials are expected to be needed in a Malone cycle system. The working fluids tested to date are particularly benign.

Supportability. Because the working fluid in a Malone cycle is similar in some respects to a hydraulic fluid, some synergism in maintenance tasks may be realized in a MASS unit. Maintenance tasks or equipment may be shared, or the presence of a hydraulic module may eliminate the need for some tools which normally would be required by an isolated Malone system.

User Needs. High pressure components may create a safety risk. Ease of operation will largely be a function of the control system, which has yet to be designed for a commercial unit.

Affordability. Development costs remain significant with this technology. Operating costs are undetermined, while procurement costs may be high if tight tolerances are required.

3.2.3.3 Comparison and Summary

As shown in Table 6, if a turbine engine is chosen as the principal power source on the MASS unit, an air cycle technology is the logical choice for a refrigeration system. The air cycle offers the smallest and simplest design and works over the widest range of ambient temperatures.

Table 6. Air Conditioner Evaluation Summary

Air Conditioning Technologies	Advantages/Strengths	Disadvantages/Weaknesses
Vapor Compression	Most common technology Many refrigerants available Easy to modularize	Some refrigerants can effect environment Narrow temperature range
Brayton Cycle (Air cycle)	Light, compact equipment Uses air as refrigerant Very wide temperature range	Low COP Requires turbine engine
Liquid Absorption	Driven primarily by heat Commercially available	Many components Complex hardware Low modularity Narrow temperature range
Solid Absorption (Metal hydride)	Few moving parts Requires little power	Uses hydrogen as working gas Narrow temperature range Relatively new technology
Liquid Compression (Malone cycle)	Compact equipment Capable of high cooling loads Wide temperature range May synergize with hydraulics Easy to modularize	Heavy equipment Tight tolerances required Very new technology; more development needed

If subsystem modularity is decisive, the air cycle should be ruled out, along with liquid absorption, in favor of an electrically powered system, such as vapor compression. Metal hydride and Malone cycle systems are promising, but may be too new for inclusion in a MASS system.

3.2.4 Energy Conversion

Energy conversion is defined as the transformation of energy into usable electrical power. Energy conversion can occur by one of four methods: electromechanical, direct, nuclear, or power conditioning (electrical converters). In most systems, some combination of these four are typically used. One example is a generator supplying the raw electrical power, with several electronic converters to manipulate the electrical power for the various ancillary equipment. The most common energy conversion setup in the current AGE is an AC generator powered by a turbine engine such as the A/M32A-60.

3.2.4.1 Applicable Technologies

3.2.4.1.1 Electromechanical

DC Generators. Typically, DC generators are used for control applications. They are discussed in detail in the following section.

Polyphase Synchronous AC Generators. Polyphase synchronous AC generators are designed for constant-speed, high efficiency applications. They are discussed in detail in the following section.

Polyphase Induction AC Generators. Polyphase induction AC generators are not appropriate for use in a MASS system due to their operating speed being slightly greater than their synchronous speed.

3.2.4.1.2 Direct

Thermoelectric Conversion. Thermoelectric conversion is the direct transformation of heat into electrical power without the use of an intermediate conversion. Its efficiency and

coefficient of performance compare unfavorably with those of conventional systems and limit its acceptability for all but small capacity or specialized systems.

Photoelectric Conversion. Photoelectric conversion is the direct production of electricity from electromagnetic radiation. Unfortunately, the photoelectric energy converter has a low individual power output and, consequently, many cells must be interconnected to attain useful power outputs. This makes the technology not appropriate for use in a MASS system because of the system's power and size constraints.

Thermionic Conversion. A thermionic power generator is a device for converting heat into electricity through the use of thermionic emission and no working fluid other than electric charge. Thermionics depend on the fact that when a material is heated, it emits electrons. The system is designed so these electrons can be utilized as electric current. Because of the state of development of the technology and the power constraints, thermionic conversion is not appropriate for use in a MASS system.

Fluidynamic Converters. Fluidynamic converters use a high-velocity, high-temperature fluid that is directly converted into electricity. This system is well-suited to large-scale applications. However, the high temperature requirements and system complexity make it inappropriate for use in a MASS system.

Fuel Cells. Fuel cells convert chemical to electrical energy isothermally and directly. They are discussed in the following section.

3.2.4.1.3 Nuclear Reactors

Nuclear to thermal energy conversion is the liberation and control of energy through nuclear reaction. Because of the safety and cost constraints, among others, nuclear power is not appropriate for use in a MASS system.

3.2.4.1.4 Power Conditioning Transformers and Inverters

A transformer is not appropriate for use in a MASS system as the primary power generating device. Transformers are capable of changing AC power's voltage, but they are unable to change its frequency characteristics. Similarly, AC to DC or DC to AC converters and inverters change the supplied power to the signal that is usable by the aircraft without adding power.

3.2.4.2 Description of Candidate Technologies

DC Generators.

Operational Parameters. Sentence 2 seems to re-state sentence 1. Could some words be added such as "A DC generator can also be considered ..."? Its construction consists of a stator main field, rotor winding, brushes, and commutator. The main field of a DC generator is produced by either passing a DC exciting current through the main field winding or by using a permanent magnet. Those generators that utilize a DC exciting current are known as wound-field DC generators and can consist of four types: separately excited, shunt, series, or compound DC generators.

The DC generator produces an output voltage that is proportional to motor speed, minus the winding losses. Due to arcing on the surface between the brushes and commutator, the speed and output current achievable by the DC generator are limited. In addition, the complexity of the DC generator results in higher construction cost and periodic maintenance.

Separately excited DC generators have the field winding connected to an independent DC supply. This type of generator permits stable operation over a very wide range of voltages. Separately excited generators are the most common type of DC generator.

Shunt DC generators have the field winding connected in parallel with the armature winding. As a result, the armature winding supplies current to the load and the field winding.

This results in some reduction of output voltage as a function of load current. The shunt DC generator is suitable for fairly constant voltage applications.

Series DC generators have the armature winding and field winding connected in series. This results in the output voltage increasing with increasing load current. Therefore, series DC generators are only suitable for special purpose applications.

The compound DC generator has both a series field winding and a shunt field winding. The shunt winding furnishes the major part of the magnetomotive force. The series winding produces a variable magnetomotive force that offers a means of compensating for voltage drop. Compound generators are used for applications requiring constant voltage.

Permanent magnet DC generators have the field winding replaced with a permanent magnet. Therefore, the stator magnetic flux remains essentially constant at all levels of armature current, and the speed-torque curve of the permanent magnet generator is linear over an extended range as compared to the wound-field type.

Evaluation Based on:

Performance. DC generators are capable of meeting the requirements for the MASS program. These generators will have to be hermetically sealed to prevent arcing on the commutator from igniting any hazardous fumes.

Deployability. Because of the brushes and commutator in the generator, and the need to hermetically seal this equipment, this generator will tend to be larger than those of other technologies.

Environmental Impact. No hazardous materials are expected to be needed for the DC generator.

Supportability. For high power applications, periodic maintenance on the generator's brushes and commutator will be required.

User Needs. Not applicable.

Affordability. DC generators are a developed technology. However, the need for brushes and commutators that can handle high power and a hermetically sealed case will increase the cost to a moderate level.

Polyphase Synchronous AC Generators.

Operational Parameters. AC generators depend on a rotating magnetic field between the rotor and stator. They are designed to convert mechanical power into AC electric power. The advantage of the AC generator over the DC generator is that the high current brushes and commutators are not present. This allows for higher speed and torque outputs from the generator.

Polyphase synchronous AC generators, or alternators, are designed for constant speed, high efficiency applications. These generators are called synchronous because their line frequency is directly related to their speed. Their construction consists of two or more armature windings on the stator and a field winding on the rotor. The field winding is supplied a constant DC current via slip rings. The output of the generator is an AC voltage that is proportional to motor speed.

An advantage of the synchronous generator is that two or more synchronous generators that are moving at the same speed can be connected in parallel. The disadvantage of the synchronous generator is that it has no starting torque because the rotating stator field passes the rotor field pole too rapidly to lock. Therefore, some means must be used to bring the rotor from standstill to the synchronous speed.

Polyphase synchronous generators are capable of providing up to 1700 megawatts.

Evaluation Based on:

Performance. Polyphase synchronous generators are capable of meeting the requirements for the MASS program. These generators are designed for high power applications that supply power to a three-phase AC power system.

Deployability. The polyphase synchronous generator will provide a compact design for the MASS program.

Environmental Impact. No hazardous materials are expected to be needed for the polyphase synchronous generator.

Supportability. No significant maintenance should be required for the polyphase synchronous generator.

User Needs. Not applicable.

Affordability. The polyphase synchronous AC generator is a mature technology. Procurement costs will be both low and stable.

Fuel Cells.

Operational Parameters. A fuel cell is an electrochemical power source that converts the chemical energy of a fuel and an oxidant directly to electricity. Electrochemical conversion is inherently more efficient and clean than the heat engine cycle since it does not involve fuel combustion. Fuel cells differ from batteries in that the reactants are stored externally to the cell rather than internally. This feature allows the electrodes to be optimized for high current density while avoiding the need for bulk storage within each electrode. Refueling is accomplished in the same manner as a heat engine, that is by refilling the storage tank.

Fuel cells can provide electrical power at about the same weight as an engine/generator set. Thus, a fuel cell power plant can be considered as a possible candidate for the primary energy source in the MASS application. Of the various types of fuel cell technologies, only the polymer exchange membrane (PEM) type fuel cell is a practical candidate. The other types of

fuel cells (alkaline, phosphoric acid, molten carbonate, and solid oxide) require long start-up and shut-down times and are not capable of cold starting without an auxiliary power source.

The proton-exchange membrane fuel cell (PEMFC) uses a proton-conducting polymeric membrane as the electrolyte and hydrogen as the fuel. PEMFCs are constructed as a planar stack assembly using platinum-coated membrane layers and bipolar plates that incorporate gas flow channels. NASA used PEMFCs in the Gemini program in the 1960s and this technology is now being adapted for use in automobiles, buses, and trains. The use of hydrogen is restrictive, but compact reformers are being developed that can convert methane, methanol, or diesel fuel into hydrogen.

Evaluation Based on:

Performance. The PEMFC operates at 176° F (80° C), but can be operated at partial load during start-up from ambient temperature. Energy efficiency is in the range of 40 to 50 percent at full load. Stack power to weight ratios of 550 watts/kilogram and power to volume ratios of 700 watts/liter have been achieved. The system power density depends on the type of fuel. Hydrogen-fueled systems require the fewest ancillary components, but the storage of hydrogen adds considerable weight due to the low storage density of compressed gas cylinders. Liquid-fueled and methane-fueled systems require a catalytic reformer and the balance of the plant is about twice the weight of the stack itself.

Deployability. PEMFC stacks are available with a continuous power rating of 25 kW. These stacks are 10 x 10 x 18 inches in size and weigh 100 pounds. The main advantage of the PEMFC for power generation is modularity. Depending on the power requirement, a number of stack modules can be connected to satisfy the total power requirement. This would allow the MASS system to be easily tailored for different support system requirements, avoiding the need for one large "do-all" power generator.

The main obstacle for deployment of PEMFCs is the fueling requirement. PEMFC stacks can operate only on hydrogen fuel. Hydrogen can be stored as a compressed gas or in the form

of a metal hydride, but the energy storage density is low. Hydrogen can be generated from other fuels such as natural gas, methanol, or diesel fuel using a catalytic reformer. However, this adds considerable size and weight to the fuel cell system and causes longer start-up times. Thus, the fuel logistics will require special attention when deploying PEMFCs.

Environmental Impact. PEMFCs generate no emissions other than water vapor. Stacks do not contain toxic chemicals and the electrolyte is not corrosive. Spent PEMFC stacks may need to be collected to recover the platinum catalyst.

Supportability. PEMFC stacks have no moving parts and are projected to last 10,000 hours before replacement. Ancillaries include common pumps, valves, heat exchangers, and filters for deionized cooling water. If a fuel reformer is included, periodic replacement of catalyst beds will be necessary.

User Needs. PEMFCs are a new technology with no operational experience in the military. Special training requirements will need to be defined. Safe handling of compressed hydrogen must be addressed.

Affordability. Current PEMFC stacks cost approximately \$5000/kW. This cost is projected to drop to \$1000/kW by the year 2000 and to as low as \$50/kW if high-rate production is achieved for the automotive market. Development costs are high, but many applications besides MASS are contributing to this effort.

Converters and Inverters.

Operational Parameters. In general, a converter or inverter is a device that converts one form of electrical energy into another form of electrical energy on a continuous basis. Any loss of energy within these systems while performing its conversion function is usually incidental to the process of energy translation. There are basically four types of electrical converters: DC to DC, AC to DC, DC to AC, and AC to AC. In each of these groups there are many types of topologies with varying degrees of cost, reliability, complexity, and efficiency.

A DC to DC converter is designed to convert a DC input voltage into a specific DC output voltage. These converters typically step-up or step-down the voltage, and control the

output voltage regulation. The exact characteristics of the converter are dependent on the specific application requirements of the system.

An AC to DC converter is similar to a DC to DC converter except that an input stage has been added to the system to rectify the input power. These input stages can range from a simple diode rectifier to a sophisticated power factor correction circuit. Depending on the application, these converters can be single or three-phase input signals.

The AC inverters are the most complex of the converter family. A DC to AC inverter is designed to convert a DC input voltage into an AC output voltage. Depending on the application, these devices are available with either single or three phase outputs. The complexity of the circuitry is dependent on the output requirements. AC inverters can be designed to generate either a square wave, quasi-sine wave, or sinusoidal output signal. For systems that do not require a low total harmonic distortion (THD), a square wave inverter may be acceptable. For those applications that do require a low THD, a sinusoidal output inverter may be needed. Making the inverter generate a more sinusoidal signal increases both the complexity and cost of the device.

An AC to AC inverter is composed primarily of two components: an AC to DC converter, and a DC to AC inverter. The input stage converts the input voltage into a constant voltage. This voltage is used by the second stage to generate the required output signal.

Evaluation Based on:

Performance. Each of the electronic converters are capable of meeting the requirements for the MASS program. The choice of converter type is dependent on the final system.

Deployability. State-of-the-art electronics allow for compact packaging.

Environmental Impact. No hazardous materials are expected to be needed for the converters.

Supportability. No significant maintenance should be required for the converters.

User Needs. Not applicable.

Affordability. The MASS program may require custom design for high power application. This may result in high development costs.

3.2.4.3 Comparison and Summary

The actual technology required for the MASS program will be dependent on the final requirements of the system. External factors, such as the power requirements of the various pieces of equipment, will determine the optimum combination of appropriate technologies. Based on the information presently known, a synchronous AC generator could be used as the primary power source, with an AC to DC converter to convert the energy into a voltage usable to any ancillary equipment that requires DC power (See Table 7).

3.2.5 Hydraulic Technologies

Hydraulic power systems are used in AGE to provide power to aircraft hydraulic systems during maintenance. Although many different items of equipment are involved in providing hydraulic power such as valves, piping, accumulators, motors, or engines, the pump drives the system and is of most interest to MASS. For this reason, this section describes technologies for pumps and does not review the other parts.

Current AGE probably uses? subject-verb agreement is AGE singular or plural? gear and vane pumps to supply the hydraulic pressure and flow. However, different manufacturers use different pumps as required for the hydraulic test stand or other equipment they are supplying.

3.2.5.1 Applicable Technologies

Piston Pumps. Piston pumps are often used in aerospace and aircraft applications where their precision parts result in a compact, high performance fluid power source. These pumps can be very efficient and are also generally more expensive than other types of pumps. Piston pumps

Table 7. Energy Conversion Evaluation Summary

Applicable Technologies	Advantages/Strengths	Disadvantages/Weaknesses
Brush DC	Generates DC voltage Linear speed-torque curve	Limited speed-torque capability Arcing on brushes and commutator Periodic maintenance required
Polyphase Synchronous AC	Generates three-phase AC voltage Constant output frequency relative to speed Requires little maintenance	No starting torque
Fuel Cell	High efficiency Modularity Low or zero emissions Low thermal signature	Limited availability High purchase cost for near-term applications Requires hydrogen as fuel or a subsystem that generates hydrogen from other fuels
Electronic Converter (Type dependent on application)	Operates from electrical power bus Compact packaging	Requires electrical energy supplied

typically generate between 3000 and 5000 psi maximum outlet pressure. They are capable of meeting MASS requirements for pressure and flow.

Gear Pumps. Gear pumps are positive displacement pumps which trap liquid between the teeth of spur or helical gears and deliver their charge to the high pressure outlet. Gear pumps are compact and inexpensive and are relatively immune to contaminants in the fluid.

Commonly, several configurations of gears are found in hydraulic pumping applications. Gear pumps typically generate between 2000 and 4000 psi maximum outlet pressure. They may be capable of meeting MASS requirements for pressure and flow.

Vane Pumps. Vane pumps are made up of an eccentrically placed rotor inside a cylindrical chamber. Longitudinal vanes slide radially in slots in the rotor. Neighboring vanes trap liquid between them as they sweep along the cylinder wall. As the rotor spins, the trapped liquid is compressed and propelled through the valve outlet. Vane pumps typically generate between 2000 and 4000 psi maximum outlet pressure. They may be capable of meeting MASS requirements for pressure and flow.

3.2.5.2 Description of Candidate Technologies

Piston Pumps.

Operational Parameters. Piston pumps operate by alternately filling and expelling liquid from a cylinder using the reciprocating motion of a precisely machined piston. The flow of liquid into and out of the cylinder is governed by one-way valves of either check valve or valve plate design. Both valve designs have unique advantages. Check valves isolate the individual cylinders so that more than one outlet pressure can be used at the same time. Valve plates are simpler to build and maintain and allow the pump displacement to be adjusted continuously without bypassing or recycling flow.

The pistons in a pump can be arranged in a number of ways. The two main categories of designs are axial piston pumps and radial piston pumps. In an axial pump the drive shaft axis and the piston cylinder axis are parallel or nearly parallel. Motion is converted from the spinning shaft to a reciprocating piston through the use of an angled “wobble” plate, or by bending the shaft at its end so that spinning provides some translational motion. In radial pumps, the piston cylinder axis are perpendicular to the drive shaft axis, and work is translated through an eccentric cam located on the shaft directly above each cylinder.

Piston pumps are often used in aerospace and aircraft applications where their precision parts result in a compact, high-performance fluid power source. These pumps can be very efficient and generally are more expensive than other types of pumps.

Evaluation Based on:

Performance. Piston pumps typically generate between 3000 and 5000 psi maximum outlet pressure. They are capable of meeting MASS requirements for pressure and flow.

Deployability. Piston pumps can be very compact. However, all hydraulic pump types are relatively small compared to other MASS components. The other parts of a hydraulic supply system can be large, however.

Environmental Impacts. Piston pumps can conform to all environmental regulations regarding hazardous materials, noise, and emissions. The selection of hydraulic fluid may be an environmental issue, but it does not affect the choice of pump technology.

Supportability. Hydraulic pumps are very durable and reliable. Because of their small size, they can be modular and easily replaced.

User Needs. Maintenance time and difficulty are low for this technology and for hydraulic pumps in general.

Affordability. Piston pumps have somewhat higher procurement costs than other pump technologies.

Gear Pumps.

Operational Parameters. Gear pumps are positive displacement pumps which trap liquid between the teeth of spur or helical gears and deliver their charge to the high pressure outlet. Gear pumps are compact and inexpensive and are relatively immune to contaminants in the fluid. They generally are capable of maximum pressures between 2000 and 4000 psi. Several configurations of gears are commonly found in hydraulic pumping applications.

Gear-on-gear pumps consist of two mating spur or helical gears of the same size. One gear is part of the drive shaft and it drives the second gear. Both gears trap liquid between their teeth and the wall of the pump housing. The liquid is not compressed as it is swept around the

gears, but is sealed off at low pressure and released at high pressure. The gears in this design must bear large stresses since they carry the entire power load of the pump.

If long helical gears are used, the flow is mainly axial and the pump is called a screw pump. In a screw pump, the fluid is pushed along in front of the mating surfaces of the two screw gears. Depending on the shape of the two gears, the liquid may be compressed as it translates, or simply sealed and delivered in constant volume packets. Screw gears are very quiet and can operate at high speeds.

Three-gear pumps are very similar to gear-on-gear pumps, but have two gears driven from one gear connected to the drive shaft. The main advantage of three-gear pumps is their very compact production of high flow rates. These pumps can act as dual pumps or high-capacity single pumps.

Gear-within-gear pumps are composed of a central spur gear which drives an internally toothed gear that has more teeth than the drive gear. As the gears turn, the conjugate motion produces sliding seals and cavities of varying size. If the planetary ring gear has only one tooth more than the driving spur gear, then the sliding seals are created naturally. If the ring gear has many more teeth, a crescent-shaped separator is used to fill most of the open space and provide a surface to seal the shifting cavities. These internal gear pumps produce less pressure, with maximum outlet between 1500 and 2000 psi.

Evaluation Based on:

Performance. Gear pumps typically generate between 2000 and 4000 psi maximum outlet pressure. They may be capable of meeting MASS requirements for pressure and flow.

Deployability. Gear pumps can be very compact. All hydraulic pump types are relatively small compared to other MASS subsystems.

Environmental Impacts. Gear pumps can conform to all environmental regulations regarding hazardous materials, noise, and emissions. The selection of hydraulic fluid may be an environmental issue, but it does not affect the choice of pump technology.

Supportability. Hydraulic pumps are very durable and reliable. Because of their small size, they can be modular and easily replaced.

User Needs. Maintenance time and difficulty are low for this technology and for hydraulic pumps in general.

Affordability. Gear pumps have low procurement costs compared to other technologies.

Vane Pumps.

Operational Parameters. Vane pumps are made up of an eccentrically placed rotor inside a cylindrical chamber. Longitudinal vanes slide radially in slots in the rotor. Neighboring vanes trap liquid between them as they sweep along the cylinder wall. As the rotor spins, the trapped liquid is compressed and propelled through the valve outlet. They can generate between 2000 and 4000 psi maximum outlet pressure.

Vane pumps are and can be configured with variable displacement, allowing fully adjustable flow from zero to maximum. Variable displacement, as opposed to bypass flow control, minimizes the power used by the hydraulic system. They are less sensitive to contaminants than piston pumps, but more sensitive than gear pumps. Leakage around the vane tips makes vane pumps poor performers at low rotational speeds. Once above their start-up speed, however, vane pumps are efficient users of power.

Most vane pumps have high bearing loads because of the unbalanced pressure forces acting on the rotor inside its cylinder. This problem can be avoided by developing two compression cycles in each revolution of the rotor. To achieve this, balanced vane pump designs place the rotor in the center of the chamber and change the shape of the chamber wall to an ellipse.

Evaluation Based on:

Performance. Vane pumps typically generate between 2000 and 4000 psi maximum outlet pressure. They may be capable of meeting MASS requirements for pressure and flow.

Deployability. Vane pumps can be very compact. All hydraulic pump types are relatively small compared to other MASS subsystems.

Environmental Impacts. Vane pumps can conform to all environmental regulations regarding hazardous materials, noise, and emissions. The selection of hydraulic fluid may be an environmental issue, but it does not affect the choice of pump technology.

Supportability. Hydraulic pumps are very durable and reliable. Due to their small size, they can be modular and easily replaced.

User Needs. Maintenance time and difficulty are low for this technology and for hydraulic pumps in general.

Affordability. Vane pumps have average procurement costs compared to other technologies.

3.2.5.3 Comparison and Summary

As Table 8 indicates, hydraulic pump technology has achieved a high level of refinement. The differences between styles are subtle, and all perform well within their design specifications. The selection between different pumps depends on details of the application such as pressure, flow, speed, size, and weight. A wide range of performance exists within each pump category. For example, an axial piston pump designed for marine or industrial use may have a power to weight ratio of 0.75 HP/lb, while another axial piston pump designed for aircraft use might have a ratio as high as 4.0 HP/lb. However, for MASS, the piston pump will be the best since it will provide the pressure and flow for all aircraft.

Table 8. Hydraulic Pump Evaluation Summary

Hydraulic Technologies	Advantages/Strengths	Disadvantages/Weaknesses
Piston Pumps	High pressure output	High cost
Gear Pumps	Low cost Insensitive to contaminants	May not provide maximum desired pressure
Vane Pumps	Low cost	Inefficient at low speeds May not provide maximum desired pressure

3.2.6 Air Compressor Technologies

Air compressors are used to develop pressurized air for use in powering air tools for maintenance, charging pneumatic systems, and for starting turbine engines on some aircraft. Both high pressure (3500 psi) and low pressure (200 psi) are supplied in currently fielded AGE.

Two types of air compressor technologies are used in AGE, piston and axial turbine. The piston compressors are used with gasoline or diesel engines or electric motors to develop the

high-pressure air used for starting jet engines such as the MC-1A, MC-6, MC-7, and MC-11. Axial turbine compressors are used with turbine engines to provide air for air cycle air conditioners such as the A/M32A-60 and the A/M32A-85.

3.2.6.1 Applicable Technologies

Centrifugal Compressors. Centrifugal compressors are capable of very high flow rates, but since they do not create positive displacement when they operate, they have difficulty attaining high pressures. Because compressor requirements for both charging aircraft pneumatic systems and operating hand tools are for high pressures at low flow rates, dynamic compressors, such as centrifugal, are not appropriate. (If start air is needed in a MASS unit, and no turbine bleed air is available, then a high-flow, dynamic compressor may be useful. Otherwise, an air storage tank will be needed to collect a large volume of compressed air and discharge it quickly for jet starting. It is difficult for any single compressor to cover both the high-pressure, low-flow applications as well as the high-flow, low-pressure ones.)

Axial Compressors. Axial compressors are very efficient multistage devices found in large turbine engines. Usually, they are not manufactured as independent units. Since axial compressors are dynamic compressors, not positive displacement, they are not suitable for the high pressures needed in a MASS assembly.

Reciprocating Piston Compressors. Reciprocating piston compressors are the most common type of positive displacement compressors. They can produce higher pressures than most other types of compressors and are considered to be a good candidate for inclusion in MASS.

Rotary Screw Compressors. Rotary screw compressors are smooth-running positive displacement compressors that commonly are found producing plant air in the range of 90 to 130 psi. They are a potential candidate for MASS air compression.

Sliding Vane Compressors. The sliding vane compressor is another type of rotary positive displacement compressor. As such it is a candidate for use in a MASS unit.

Liquid Piston Compressors. Liquid piston compressors are similar to sliding vane compressors. Fixed, forward-turned vanes are used, and trapped liquid completes the enclosure when the vanes cannot reach the outer wall. Liquid piston compressors are also positive displacement compressors and are considered for MASS use in the discussion below.

3.2.6.2 Description of Candidate Technologies

Reciprocating Piston Compressors.

Operational Parameters. Piston compressors operate in the reverse manner of a piston engine. Shaft torque, from a crankshaft, delivers energy to the gas trapped in each of several cylinders. Valves in each cylinder chamber are synchronized to allow low pressure gases to enter and compressed gases to leave. Since the gas in a reciprocating piston compressor is isolated and then compressed one cylinder volume at a time, piston compressors are one type of positive displacement compressor.

Reciprocating compressors have capacities up to 15,000 cfm and discharge pressures up to 60,000 psig. Most applications fall between 10 and 300 psig and require less than 2500 cfm. Single-acting compressors use only one side of the piston to compress gas, while double-acting compressors use both sides. Compressors under 50 HP usually are single-acting and those over 50 HP are more likely to be double-acting. Single stage compressors are only used up to 80 psig. Intercooling between stages can be implemented to reduce the power needed to achieve high pressures in multistage compressors.

Due to the high speeds of sliding contact present between pistons and their cylinders, reciprocating compressors usually are lubricated with oil. When lubrication is used, some amount of oil vapor will be present in the compressed gas. This can be a problem if the gas being compressed reacts chemically with the oil, as do some refrigerants, or if the compressed gas needs to be clean, such as breathing air. A downstream filter, to collect both oil and water, usually will provide sufficiently clean and dry compressed gas for most uses.

Reciprocating and rotary screw compressors are equally common producers of typical plant air at 90 to 110 psig. However, when pressures over 200 psig are needed, reciprocating compressors generally are chosen.

Evaluation Based on:

Performance. Reciprocating piston compressors are commercially available in the sizes required for MASS use. They provide high pressures at relatively low flow rates. Their capacity is degraded somewhat at higher altitudes, where the air is less dense, because of the clearance volume present in each cylinder. The high pressure air tank that holds the compressed air before it is used makes the system susceptible to battle damage. Piston designs are very mature and borrow some of their advances from piston engine work.

Deployability. Reciprocating compressors are more compact in multi-stage configurations than other positive displacement compressors. However, most of the volume of a compressor system resides in the storage tank, which provides a reservoir of compressed air for various end uses. If high flow rates are needed, this tank must be quite large. All positive displacement compressors require some kind of reservoir to smooth out their intermittent flow.

Environmental Impacts. Piston compressors are louder than rotary machines. No hazardous materials or emissions are generated by reciprocating piston compressors.

Supportability. Reciprocating compressor designs are very reliable. However, they produce relatively high levels of vibration which can damage the compressor itself, or other MASS equipment, if not properly isolated. Maintaining sufficient lubrication and checking pressure gauges are the primary support activities associated with air compressors. Piston compressors are common pieces of equipment that do not require any unusual maintenance practices and are easy to replace. They easily can be made modular using a separate power supply.

User Needs. Reciprocating piston compressors are proven, reliable machines capable of meeting user needs related to air compression. The presence of a high-pressure air tank presents a risk of explosion.

Affordability. Procurement costs are low for piston compressors and development costs are not required. Reliable designs are available which will keep operating and life cycle costs to a minimum.

Rotary Screw Compressors.

Operational Parameters. Rotary screw compressors operate by pushing gas along a helical cavity which changes volume as the helical rotor turns. Screw compressors create positive displacement by sealing off the helical cavity between mating rotor threads before the gas is allowed to escape through the exhaust port. In twin screw compressors, the two screws are not the same size, and they therefore must rotate at different speeds, in the range of 2000 to 4000 rpm. The flow of gas is mainly axial as one screw drives another, directly or with timing gears.

The efficiency of screw compressors range from 70 to 88 percent. Accuracy in manufacturing rotors is critical to achieving high efficiency. In heat pump applications, reciprocating compressors lose volumetric efficiency as the outside temperature drops because of the increased influence of the clearance volume. Screw compressors are advantageous in these situations because they have no clearance volume. The lack of clearance volume also helps the screw compressor maintain its capacity at high altitudes.

Screw compressors can be designed with or without lubrication. Oil-free designs must be cooled and may have to run at lower speeds, but the lack of lubricant simplifies maintenance. Usually, oil-free designs are chosen when the pressurized air must be free of oil.

Twin screw compressors are found in many industrial and commercial refrigeration applications. They commonly provide pressure ratios between 7 and 8, in a single stage, and are capable of ratios as high as 20. Screw compressors dominate the portable compressor market and share the plantair market equally with reciprocating compressors up to about 3000 cfm.

Evaluation Based on:

Performance. Usually, screw compressors are not used in multi-stage configurations needed to generate pressures greater than about 200 psi. However, they are compact and efficient. They have no clearance volume and they run smoothly with less vibration and noise than piston compressors. Since they are also positive displacement compressors, they require a storage tank to collect the compressed air before it is used. The storage tank makes all positive displacement compressors susceptible to battle damage. Screw compressors rely on mature technology that is commonly available.

Deployability. Most of the volume of a compressor system resides in the storage tank which provides a reservoir of compressed air for various end uses. If high flow rates are needed, this tank must be quite large. All positive displacement compressors require some kind of reservoir to smooth out their intermittent flow.

Environmental Impacts. No hazardous materials or emissions are generated by rotary screw compressors, and they run more quietly than reciprocating compressors.

Supportability. Screw compressors are reliable and can be designed with or without lubrication. Oil-free designs must be cooled and may have to run at lower speeds, but the lack of lubricant simplifies maintenance. Screw compressors are common pieces of equipment which do not require any unusual maintenance practices and are easy to replace. Their modularity is limited by their need for shaft torque to drive them.

User Needs. Rotary screw compressors are proven, reliable machines. However, the presence of a high-pressure air tank presents a risk of explosion and an associated safety risk.

Affordability. Procurement costs are low for screw compressors, and development costs are not required. Reliable designs are available which will keep operating and life-cycle costs to a minimum.

Sliding Vane Compressors.

Operational Parameters. Sliding vane compressors are composed of an eccentrically placed circular rotor located in a cylinder. Longitudinal vanes slide radially in slots in the rotor, maintaining continuous contact with the cylinder wall. In this way, a set of cavities is created whose size expands and contracts with the rotation of the off-center rotor. Inlet and exhaust ports are positioned in the cylinder wall to admit gas when the cavities expand and collect gas after the cavities contract. Since the cavities do not exchange gas, sliding vane compressors are considered positive displacement machines.

Sliding vane compressors may be dry, lubricated, or oil-flooded. Compressors up to 150 psig and 900 cfm, using two rotary vane stages, have been used in portable compressors. However, this compressor style generally is not used for applications over 100 cfm.

Evaluation Based on:

Performance. Like screw compressors, sliding vane compressors typically are not found in capacities greater than 250 psi. The air storage tank makes all positive displacement compressors more susceptible to battle damage. Sliding vane compressors rely on mature technology that is commonly available.

Deployability. Most compressor system volume resides in the storage tank, which provides a reservoir of compressed air for various end uses. If high flow rates are needed, this tank must be quite large. All positive displacement compressors require some kind of reservoir to smooth out their intermittent flow.

Environmental Impacts. No hazardous materials or emissions are generated by sliding vane compressors, and they run more quietly than reciprocating compressors.

Supportability. Rotary vane compressors are reliable and can be designed with or without lubrication. Oil-free designs must be cooled and may have to run at lower speeds, but the lack of lubricant simplifies maintenance. Screw compressors are common pieces of

equipment which do not require any unusual maintenance practices and are easy to replace. Their modularity is limited by their need for shaft torque to drive them.

User Needs. Sliding vane compressors are proven, reliable machines. The presence of a high-pressure air tank presents a risk of explosion and an associated safety risk.

Affordability. Procurement costs are moderate for sliding vane compressors, but some development costs may be needed to create a design suitable for MASS.

Liquid Piston Compressors.

Operational Parameters. Liquid piston compressors are another type of rotary positive displacement compressor. In these machines, a forward-turned ring of blades rotate in an elliptical chamber. Liquid is present along the inner chamber wall and fills the space between the elliptical chamber and the circle of blades. As the radius of the ellipse reaches a minimum, liquid trapped between adjacent blades acts like a piston and compresses the gas before it escapes through an outlet port. Inlet ports are located where the radius is large, the liquid retreats, and more gas can enter. As in the rotary vane design, the inlet and outlet ports are fixed and valveless. In the liquid piston design, however, the inlets and outlets are located in a central cone in the middle of the chamber.

Evaluation Based on:

Performance. Liquid piston compressors typically are not found in capacities large enough to meet MASS requirements. The air storage tank makes all positive displacement compressors more susceptible to battle damage. Liquid piston compressors commonly are not available from commercial sources.

Deployability. Most compressor system volume resides in the storage tank, which provides a reservoir of compressed air for various end uses. If high flow rates are needed, this

tank must be quite large. All positive displacement compressors require some kind of reservoir to smooth out their intermittent flow.

Environmental Impacts. No hazardous materials or emissions are generated by liquid piston compressors, and they run more quietly than reciprocating compressors.

Supportability. The use of a fixed amount of liquid inside the compressor cylinder is expected to make maintenance more difficult. Leaks or losses through the outlet may lead to the challenging task of refilling the chamber to its optimum working level. Degradation of performance due to slow leakage may be hard to detect. Replacement of parts also may be difficult due to the rarity of this technology in commercial applications.

User Needs. Unusual maintenance tasks are expected to be associated with liquid piston compressors. The presence of a high-pressure air tank presents a risk of explosion and an associated safety risk.

Affordability. Procurement costs are uncertain for liquid piston compressors, and development costs would be needed to create a design suitable for MASS.

3.2.6.3 Comparison and Summary

To meet the high-pressure, low-flow requirements of the MASS unit, a positive displacement compressor must be used. The most common type of positive displacement compressor, and the one best suited for pressures over 200 psi, is the reciprocating piston compressor. Rotary compressor designs operate with lower levels of vibration but generally are not used to generate very high pressures. The multistage arrangements needed to achieve very high pressures result in large, disjointed hardware in most rotary designs, while multicylinder piston compressors are as common and compact as an automobile engine (See Table 9).

Table 9. Air Compressor Evaluation Summary

Compressor Technologies	Advantages/Strengths	Disadvantages/Weaknesses
Reciprocating Piston Compressors	Multistage designs common Familiar hardware	Capacity drop at high altitudes
Rotary Screw Compressors	Low vibration No clearance volume	No multistage designs
Sliding Vane Compressors	Low vibration	No multi-stage designs
Liquid Piston Compressors	Low vibration	Uncommon hardware Potential for leaks

3.2.7 Lighting Technologies

Current AGE provides floodlights for maintenance work around aircraft. These are high capacity units needing a high light output to power input ratio. The NF-2 light cart uses mercury vapor lamps, while the NF-2D uses high-pressure sodium lamps.

3.2.7.1 Applicable Technologies

Incandescent. Incandescent lamps produce light using an electrically conducting filament inside a chamber of inert gas. These lamps are inefficient users of power and lead to high operating costs.

Halogen. Halogen lamps provide slightly greater illumination than incandescent lamps but at the cost of shorter average life. Incandescent lamps gradually dim due to evaporation of the tungsten filament. The evaporated tungsten blackens the glass bulb and leaves a thinner filament. In this way, incandescent lamps can lose up to half of their original brightness. Halogen lamps produce incandescent light through a tungsten filament placed in a compact quartz chamber of halogen vapor. The halogen atmosphere continuously returns the evaporated tungsten particles to the filament. This prevents the glass from darkening. Unlike other incandescents, halogen lamps retain their light intensity extremely well.

Fluorescent. Fluorescent lamps give off visible light using a phosphor coated tube that is excited internally by ultraviolet light. A small amount of mercury is used to develop the ultraviolet light on the inside of the tube. Fluorescent lamps are more energy efficient and last longer than incandescent or halogen lamps, but they require a large bulb surface area to produce high levels of illumination. This makes them impractical for the MASS application.

Mercury Vapor. Mercury vapor lamps are composed of a quartz arc tube filled with mercury and argon and surrounded by nitrogen. The arc tube is maintained at a high operating temperature and gives off radiation in visible bluish green and ultraviolet light, according to the mercury emission wavelengths. The outermost glass surface is coated with a phosphor to convert the ultraviolet light into additional visible light. Mercury vapor lamps require time to warm up the arc tube and are not as efficient as other types of high-intensity discharge lamps. Until recently, mercury vapor lamps were used for aircraft ground support in the NF-2 floodlight set. Because of insufficient illumination (45,000 lumens with two lamps), the NF-2 set is being replaced by the NF-2D, which uses two high pressure sodium lamps to generate 140,000 lumens.

Metal Halide. Metal halide lamps, also called multivapor lamps, are similar to mercury vapor lamps but are improved by the addition of small quantities of other gases to the mercury and argon inside the arc tube and by the replacement of the nitrogen layer with a vacuum region. The mixture of gases produces a whiter light than mercury vapor due to the variety of emission spectra represented. Metal halide lamps are also highly efficient, offering over 80 lumens per watt of electricity. They are considered a potential candidate for MASS use.

High-Pressure Sodium. High-pressure sodium lamps are made up of a translucent aluminum oxide arc tube containing metallic sodium and gaseous xenon, sodium, and mercury. A vacuum is maintained around the arc tube to provide thermal insulation. These lamps have excellent lumen maintenance and long life, which lead to low operating costs. They also are very efficient, giving at least 75 lumens per watt. High-pressure sodium lamps are currently used in AGE equipment and are a strong candidate for inclusion in a MASS unit.

Low-Pressure Sodium. Low-pressure sodium lamps are the most energy-efficient light source available. They have long life, low operating temperatures, and provide the lowest

operating costs of any lighting technology. However, they generally are not sold in sizes over 200 watts. Because of their high efficiency, they are a candidate for inclusion in a MASS system.

3.2.7.2 Description of Candidate Technologies

Metal Halide.

Operational Parameters. Metal halide, (also called multivapor) lamps are improved over mercury vapor lamps by the addition of small quantities of other gases such as sodium, thallium, and scandium to the mercury and argon inside the quartz arc tube, and by the replacement of the nitrogen layer with a vacuum region. The mixture of gases produces a whiter light than mercury vapor due to the variety of emission spectra represented. Metal halide lamps are highly efficient, delivering over 80 lumens per watt of electricity.

Like fluorescent lamps, high-intensity discharge lamps, such as metal halide and high-pressure sodium, require ballast circuits in their wiring to balance the power factor of the lighting system.

Metal halide lamps can cause serious burns from shortwave ultraviolet radiation in the event of a broken or punctured outer shell. However, lamps are available with a self-extinguishing feature that turns off the lamp after the outer shell is broken.

Evaluation Based on:

Performance. Metal halide lamps are less efficient than sodium lamps, but are available in higher power so two bulbs can still meet MASS lighting needs. More power is needed to run metal halide lights of the same luminosity.

Deployability. Because only two lamps are needed to meet the lighting requirements, the size of the lighting module is minimized when using this technology.

Environmental Impacts. Broken lamps can release some gaseous metals into the air. However, the volume contained in each lamp is so small that neither safety nor disposal should be a significant issue.

Supportability. Because of their high watt rating, metal halide lamps can provide enough light output for the MASS application with only two high-powered lamps. All considered lighting systems are highly modular and require very little training.

User Needs. Metal halide lamps provide good color rendering, which can allow easier maintenance on color coded wiring illuminated by these lamps. Metal halide lamps can cause serious burns from shortwave ultraviolet radiation in the event of a broken or punctured outer shell. However, certain lamps are available with a self-extinguishing feature that turns off the lamp after the outer shell is broken.

Affordability. Metal halide lamps have lower procurement costs but slightly higher operating costs than other lighting technologies.

High-Pressure Sodium.

Operational Parameters. High-pressure sodium lamps are made of a translucent aluminum oxide arc tube containing metallic sodium and gaseous xenon, sodium, and mercury. A vacuum is maintained around the arc tube to provide thermal insulation.

High-pressure sodium lamps, like metal halide lamps, require ballast circuitry to balance the power factor of the lighting system. They are very efficient, giving at least 75 lumens per watt. These lamps have excellent lumen maintenance and long life, which lead to low operating costs. However, their light output decreases somewhat when they are used at high altitudes where atmospheric pressure is low.

High-pressure sodium lamps were selected to replace mercury vapor lamps in the redesigned AGE floodlight set NF-2D. The new design uses two 1000-watt lamps to deliver over 140,000 lumens. This more than doubles the output of the NF-2, which used mercury vapor lamps.

Evaluation Based on:

Performance. High-pressure sodium lamps currently are specified in the NF-2D floodlight set. In that system, two 1000-watt high-pressure sodium lamps meet the design requirement of 140,000 total lumens and provide more than adequate lighting for night maintenance operations.

Deployability. Since only two lamps are needed to meet the lighting requirements, the size of the lighting module is minimized using this technology.

Environmental Impacts. Broken lamps can release some gaseous metals into the air. However, the volume contained in each lamp is so small that neither safety nor disposal should be a significant issue.

Supportability. High pressure sodium lamps average long lives, ranging from 10,000 hours to over 24,000 hours. Long lamp life reduces the need for maintenance. All lighting systems considered are highly modular and require very little training.

User Needs. High-pressure sodium lamps meet all user needs related to ground support lighting systems, as illustrated by their selection in the NF-2D. They provide high lumen output with little degradation over a long life. Colors illuminated by these lamps appear slightly yellow.

Affordability. High-pressure sodium lamps have low procurement costs and low operating costs.

Low-Pressure Sodium.

Operational Parameters. Low-pressure sodium lamps operate at about two times atmospheric pressure compared to eight to ten atmospheres in high-pressure lamps. They are more energy efficient than high-pressure sodium lamps, but they require larger tubes to contain their vapor at a lower pressure.

These lamps have excellent lumen maintenance and long life, which lead to low operating costs. Efficiency and luminosity are maintained at high altitudes better than other types of lights. Like other high-intensity discharge (HID) lamps, low-pressure sodium lamps require ballast circuitry to balance the power factor of the lighting system.

Low-pressure sodium lamps are the most energy-efficient light source available. They have long life, low operating temperatures, and provide the lowest operating costs of any lighting technology. However, they generally are not available in sizes over 200 watts.

Evaluation Based on:

Performance. With respect to energy use, low-pressure sodium lamps are the most efficient technology available. However, their large size and low watt rating per bulb make them more susceptible to damage. Sodium lamps are a relatively new technology and are the culmination of much R&D effort. New advances are not likely to improve this technology.

Deployability. Low-pressure sodium lamps are much larger than their high pressure counterparts. Because of their lower available wattage, six to ten lamps would be needed to meet the requirements for illumination. These two factors significantly reduce the deployability of low pressure sodium lamps.

Environmental Impacts. Broken lamps can release some gaseous metals into the air. However, the volume contained in each lamp is so small that neither safety nor disposal should be a significant issue.

Supportability. The large size of a low-pressure lighting system reduces the options for modularity in the MASS concept. The lifetime of a low-pressure lamp is good, but since more lamps will be needed to meet lighting requirements, the maintenance rate may be higher than for other lighting technologies.

User Needs. Sodium lamps maintain their light output very well throughout their lifetimes. Color rendering, however, is even worse in low-pressure sodium lamps than high-pressure sodium lamps. Low-pressure sodium lamps produce a yellowish light.

Affordability. Low-pressure sodium lamps have higher procurement costs than other light sources, but their operating costs are low.

3.2.7.3 Comparison and Summary

As shown in Table 10, high-pressure sodium lamps appear to be the most suitable technology to meet the requirements of a MASS lighting system.

Table 10. Lighting Evaluation Summary

Lighting Technologies	Advantages/Strengths	Disadvantages/Weaknesses
Metal Halide	Good color rendering	Lumen output drops with time UV exposure risk if broken
High-Pressure Sodium	Proven in AGE equipment Maintains lumen output with time	Poor color rendering Output decreases at altitude
Low-Pressure Sodium	Highest energy efficiency Maintains lumen output with time Maintains output at altitude	Low maximum wattage Poor color rendering Large bulb dimensions

3.2.8 Nitrogen Generation

Nitrogen is used for filling fuel bladders as the fuel is removed to make sure that an inert atmosphere is in the bladder to reduce the chance of fire. It is also used for servicing aircraft tires, struts, accumulators, and certain missile systems. Current AGE need another word to make this subject appear plural such as NSU-L75 are merely storage vessels on wheels for liquid or gaseous nitrogen.

3.2.8.1 Applicable Technologies

Hollow Fiber Membrane. The hollow fiber membrane separation method of nitrogen generation takes advantage of different rates of diffusion to separate nitrogen from oxygen in air. If oxygen can be used, this method is appealing because it results in two useful fluid streams: nitrogen and oxygen. Purities up to 99.9 percent nitrogen can be achieved using this method. Currently, aircraft ground support equipment uses this technology; therefore, it is a likely candidate for inclusion in a MASS system.

Pressure Swing Adsorption. Pressure swing adsorption technology uses preferential adsorption to separate nitrogen and oxygen in air. Adsorption takes place in a carbon or zeolite molecular sieve, which traps oxygen and other components of air while allowing nitrogen to flow through. Purities up to 99.9995 percent nitrogen can be achieved using this method. It is a potential candidate for MASS system use.

Oxygen Combustion. Oxygen combustion does not produce pure nitrogen. Instead, it produces noncombustible, oxygen-free gas by pre-igniting the oxygen in the air at precise stoichiometric conditions. The resulting gas is similar to an exhaust, or flue gas, containing a variety of hydrocarbon compounds in addition to nitrogen. Because the need for nitrogen is usually a response to flammability and combustibility concerns, using an oxygen-depleted gas may meet that need at a lower cost than pure nitrogen. For this reason, oxygen combustion is a candidate technology.

Pressurized Gas Cylinders. Pressurized bottles of nitrogen can be used if the required gas volume is not too great. Most flight-line nitrogen needs currently are met using pressurized bottles. This technology is considered as a baseline system for nitrogen in a MASS unit.

Liquid Nitrogen. Storing nitrogen in liquid form prior to use is a compact solution in certain applications. As with gas cylinders, frequent replacement is a logistical problem for a portable unit like MASS. Additional obstacles are presented by the refrigeration requirements of storage. For these reasons, liquid nitrogen storage will not be considered for MASS.

3.2.8.2 Description of Candidate Technologies

Hollow Fiber Membrane.

Operational Parameters. This method of separating the components of air uses a diffusion process to trap the slowly diffusing nitrogen molecules in a hollow fiber membrane, allowing the other gases to pass through. Special plastics, formed into thin tubes like horsehair, are bundled together in a parallel arrangement inside the membrane generator. The diffusion process works best at pressures between 100 and 200 psi. For this reason, the nitrogen separation typically occurs between stages of a multistage compressor. An oversized, multi-stage compressor provides the driving force for the generation of pressurized nitrogen. Downstream of the fiber membrane, the pressure is unchanged, but the mass of the flow stream has been reduced. To achieve a purity of 99.5 percent nitrogen, 60 percent of the inlet flow must be rejected. Therefore, the high-pressure stages of the compressor have smaller displacements than the early stages.

Evaluation Based on:

Performance. Hollow fiber membrane technology can meet the flow rate and purity requirements of MASS nitrogen generation. Purities up to 99.9 percent nitrogen can be generated continuously from air, as long as power is supplied to the compressor. The nitrogen yield (40 percent yield at 99.5 percent purity) can be increased if lower purity is allowed. This technology is passive and supplies a continuous stream of nitrogen.

Deployability. Membrane separators are the most compact technology available. Not including the compressor, a membrane unit of roughly 3 cubic feet can handle 40 cfm of nitrogen.

Environmental Impacts. Other than the fuel burned to power the compressor, no emissions result from the hollow fiber membrane process.

Supportability. Hollow fiber membrane separation is a continuous process requiring very little attention. The membrane is not depleted with use, so it has a very long life.

User Needs. Since the membrane separator is a passive element, the compressor is the only part of the nitrogen generation system that requires regular adjustment by the user. This technology has been demonstrated to meet user needs in existing ground support equipment.

Affordability. Procurement costs for membrane systems are lower than adsorption systems, but higher than inert gas generators. Operating costs are slightly higher than adsorption, because more energy is used to generate the same flow rate.

Pressure Swing Adsorption.

Operational Parameters. Pressure swing adsorption (PSA) technology uses preferential adsorption to separate nitrogen and oxygen in air. Adsorption takes place in a molecular sieve that traps oxygen and other components of air but allows nitrogen to flow through. To purge the contaminants from the adsorption bed, a pressure swing is initiated periodically to back-flush the sieve.

To extend the life of the sieve material, upstream filtering and drying of the inlet stream are recommended. Drying can be done through moisture condensation onto refrigerated surfaces or by using a chemical desiccant. Hydrocarbons must be removed carefully from the inlet stream or they will stick to the surface of the sieve material, reducing its filtering capacity. Purities up to 99.9995 percent nitrogen can be generated using this technology. To achieve higher flow rates while maintaining constant purity, equipment size must increase dramatically.

Evaluation Based on:

Performance. PSA systems require less energy and less inlet air volume to generate nitrogen than hollow fiber membrane separators. High purity is achieved using this technology;

however, flow rates are usually low. Like hollow fiber membranes, molecular sieves can operate indefinitely if the inlet filters are replaced regularly.

Deployability. PSA systems must be much larger than hollow fiber membrane systems to provide the same flow rate. Size is expected to be the crucial factor, limiting the applicability of this technology.

Environmental Impacts. Other than the fuel burned to power the compressor, no emissions result from the pressure swing adsorption process.

Supportability. Pressure swing adsorption is a continuous process which requires very little attention. The periodic purging of the molecular sieve is handled automatically. The molecular sieve is not depleted with use, so it has a very long life.

User Needs. The air compressor upstream and downstream of the molecular sieve are the primary maintenance items for this technology. Regular replacement of filters is a quick and simple operation. The controls that regulate the periodic pressure swings are the only unique component that could require special procedures.

Affordability. Procurement costs are high for this technology, but operating costs are low.

Oxygen Combustion.

Operational Parameters. Oxygen combustion does not produce pure nitrogen. Instead, it produces an inert gas suitable for blanketing or purging flammable or combustible vapors. The inert gas is made of the combustion products of natural gas, propane, or other fuel. The components of the inert gas depend on the stoichiometry of combustion, which can be adjusted to lower oxygen concentrations. Burning in a reducing atmosphere drops the outlet oxygen concentration from about 0.6 percent to 500 ppm while increasing the concentrations of CO and H₂ from 0.01 percent to 0.6 percent. CO₂ concentrations in the outlet gas are 11.4 percent for natural gas firing and 13.7 percent for propane fuel. Water vapor may also be present at up to

100 percent relative humidity in the case of an open water cooling system. If necessary, H₂O and CO₂ can be stripped from the inert gas in a downstream drying tower.

The most compact arrangement of equipment for producing inert gas through combustion is a vertical combustion chamber over an open water sump. The hot gas is cooled quickly as it evaporates water ? a counter-flowing mist. Corrosion is minimized using this method, since oxides of nitrogen are not allowed to form. To operate the system, it must be on a level surface and be supplied with water, electricity, and fuel.

Evaluation Based on:

Performance. The oxygen combustion technique of inert gas generation is the lowest cost method of producing inert gas. Large volumes of inert gas can be generated and compressed using this technology. The acceptability of CO₂ in the final product must be evaluated with this method, as removing it adds to system size, cost, and complexity. The need for several fluid streams such as cooling water, fuel, and condensate makes this technology more susceptible to battle damage than separation technologies. However, this system does not operate at higher pressures, which reduces the likelihood of battle damage. Also, the use of liquid water may create problems in cold environments. The combustion method is a simple and mature technology that is not likely to change in the future.

Deployability. A compact system for inert gas generation at 40 cfm weighs about 1700 pounds, is 8 feet long, 3 feet wide, and 9 feet tall. The height of a combustion system is determined by the combustion chamber, which utilizes falling water sprays over an open pool of water to cool the counter-flowing combustion gas. Horizontal, water-jacketed combustion chambers result in larger system volumes and weights.

Environmental Impacts. This technology burns more fuel than other gas generating methods because fuel is used to create an exhaust gas stream and, like the other technologies, it is used to generate power to run the compressor.

Supportability. Three additional fluid streams must be supplied to utilize this technology. First, the fuel to be burnt in the creation of inert combustion products must be provided. Second, cooling water must be circulated to remove the heat of combustion from the gas. Third, condensation of liquid water must be removed as the humid gas cools. These fluid streams all add to the complexity of the system, increasing support requirements and reducing modularity.

User Needs. The potential for freezing hoses, broken pipes and connections is greater with this technology since more fluid flows are used. Training complexity and time to troubleshoot problems also may be high. The separate tank of gaseous fuel and need for flame inside the combustor are additional safety risks.

Affordability. This is the lowest cost generation technology with regard to procurement. Operating costs depend on the expense required to purchase and transport fuel.

Pressurized Gas Cylinders.

Operational Parameters. The traditional method of providing compressed nitrogen gas on the flightline is to supply enough tanks of pressurized nitrogen to meet aircraft maintenance needs. While this method reduces the amount of equipment that must be maintained, it demands accurate planning of nitrogen demand.

Evaluation Based on:

Performance. Pressurized nitrogen cylinders are a simple and reliable source of nitrogen for flight-line use. They provide sufficient pressure and volumes of nitrogen to charge aircraft systems. They are not replenishable on the flight-line, however, and spare tanks are bulky.

Deployability. The need to deploy sufficient nitrogen is the major drawback of this technology. Most current nitrogen AGE involves dedicated hand carts, each carrying two tanks of nitrogen at 3500 psi.

Environmental Impacts. No emissions are produced and no energy is required at the site of the AGE for pressurized nitrogen. The work of separating nitrogen from air is done beforehand.

Supportability. In this method, there is no equipment to break down; however, empty bottles must be replaced regularly with full ones. Long-duration logistical problems may arise during long deployment times.

User Needs. Users are well served by this technology because it is simple and predictable. No special skills or training are needed to access the nitrogen supply. The need to deploy many pre-pressurized tanks increases the safety risk associated with tank rupture.

Affordability. Procurement costs are negligible with this method; however, regular tank replacement raises operating costs. Low maintenance keeps overall costs relatively low.

3.2.8.3 Comparison and Summary

Pressurized bottles of nitrogen are not recommended due to their poor deployability. A continuous method of gas generation is preferred.

Hollow fiber membrane separation offers the best combination of purity, flow rate, and equipment size for generating nitrogen in MASS. PSA technology selected for laboratory systems where extremely high purity nitrogen is required for accurate experimental data. Industrial processes such as blanketing and purging combustible gases generally can be performed with lower purity gases produced by membrane separation or inert gas generation. Since increased purity reduces the flow rate, equipment is selected to give the lowest purity necessary. All generation systems require some compression after the desired gas composition is achieved (see Table 11).

Table 10. Nitrogen Generation Evaluation Summary

Nitrogen Technologies	Advantages/Strengths	Disadvantages/Weaknesses
Hollow Fiber Membrane	Continuous flow Passive system	Requires compressed air
Pressure Swing Adsorption	Highest purity nitrogen Passive system	High initial cost Low flow rate Intermittent flow
Oxygen Combustion	Low equipment cost	Separate "clean" fuel supply Complex equipment CO ₂ removal is optional extra Tall dimensional envelope
Pressurized Cylinders	Low cost No moving parts	Must be replaced frequently

3.2.9 Batteries

Battery technology is useful for MASS for starting the system and providing power for propulsion when the main power supply is not in use. Batteries are provided on all engine-driven AGE for start-up power and, in some cases, for other backup requirements.

3.2.9.1 Applicable Technologies

Because of the low energy density of batteries, they are not practical for use as a primary energy source for the MASS application. For example, to deliver 75 kW for four hours would require 20,000 pounds of lead-acid or nickel-cadmium batteries, about six times the weight of an A/M32A-60A power cart (3340 pounds). Even primary (nonrechargeable) lithium batteries, which have the highest energy density of all battery types, would be consumed at the rate of 3500 pounds every 4 hours at this power level. In contrast, generating 75 kW of electricity for four hours using an engine/generator set would require only 50 pounds of diesel fuel. Thus, power sources other than batteries are far more suitable for the MASS application. Batteries are

applicable, however, for short-duration, high-power usage such as engine starting or peak power delivery. Batteries with high-power density are the most suitable here. Candidate technologies with high power density include lead-acid and nickel-cadmium batteries. Nickel-metal hydride, lithium-ion, lithium-polymer, and zinc-air batteries can be ruled out because they do not possess adequate power capability, even though their energy density exceeds that of lead-acid and nickel-cadmium batteries.

An alternative to batteries for peak power delivery is the ultracapacitor. Ultracapacitors have a power density much greater than a battery but with a lower energy density. Thus, for short duration (i.e., on the order of 15 to 30 seconds), ultracapacitors can deliver the same power level as a battery in a much smaller, lighter package. Ultracapacitors can be used in parallel with a battery or a primary energy source to provide short bursts of high power. This type of hybrid usage is being developed for hybrid electric vehicle applications.

3.2.9.2 Description of Applicable Technologies

Lead-Acid.

Operational Parameters. The cell of a lead-acid battery contains an anode of lead (Pb), a cathode of lead dioxide (PbO₂), and an electrolyte of sulfuric acid and water. As the cell is charged, the sulfuric acid (H₂SO₄) concentration increases and becomes highest when the cell is fully charged. Likewise, when the cell is discharged, the acid concentration decreases and becomes most dilute when the cell is fully discharged. The sulfuric acid electrolyte imparts a high conductivity to the lead-acid cell, which contributes significantly to its excellent high rate capability.

There are two basic cell types: vented and recombinant. Vented cells have a flooded electrolyte, and the hydrogen and oxygen gases generated during charging are vented from the cell container. The loss of gases causes the electrolyte level to drop over time, so periodic maintenance is required to replenish the water. Vented, maintenance-free batteries have become

common in recent years. These batteries still have a flooded electrolyte, but the cells are designed with a low rate of gassing so that the initial electrolyte reserve is sufficient to last the life of the battery. This battery type normally is used only in vehicular applications, however.

Recombinant cells have a starved or gelled electrolyte, and the oxygen generated during charging diffuses from the positive electrode to the negative electrode where it recombines to form water. The recombination reaction suppresses hydrogen evolution at the negative electrode, thereby allowing the cell to be sealed. Water loss is thus prevented, and the cells do not require water replenishment. In practice, the recombination efficiency is not 100 percent, and a resealable valve is required to regulate the internal pressure at a relatively low value (generally below 10 psig). For this reason, recombinant lead-acid cells are often called “valve-regulated lead-acid” (VRLA) cells.

Evaluation Based on:

Performance. Lead-acid batteries generally are rated at 77° F (25° C) and operate best around this temperature. Exposure to low ambient temperature results in performance decline, whereas exposure to high ambient temperatures results in shortened life. The temperature limits are typically -40° F to +158° F (-40° C to +70° C) for storage and -22° F to +140° F (-30° C to +60° C) for operation.

The peak power available from a lead-acid battery depends mainly on its internal impedance. High rate cells, for example, are designed specifically to have very low internal impedance as required for starting engines and auxiliary power units (APUs). The peak power density for these types of batteries can be as high as 500 W/kg at room temperature. At lower temperatures, the peak power capability drops considerably. At 0° F (-18° C) for instance, a derating factor of 50 percent is typical (i.e., 250 W/kg).

Advanced lead-acid batteries are being developed with significantly improved high-rate performance characteristics. Bolder Technologies, for instance, has developed a thin metal film (TMF) sealed lead-acid cell that has an exceptional peak power capability of 1200 W/kg. This value is about 2.5 times higher than standard high-rate designs, resulting in a significant size and

weight reduction for equivalent performance. Currently, only small cell sizes (e.g., C-size) are available, but larger cells are being developed.

Another type of advanced lead-acid battery is the bipolar lead-acid battery, under development by Arias Research, Johnson Controls, and Trojan. Power density improvement of 50 to 100 percent versus standard lead-acid batteries is being projected. These batteries are still under development, and may not be commercially available for use in the MASS application.

Deployability. Lead-acid batteries are available in a wide variety of size and form factors. A common battery used in AGE is rated at 24V/30Ah. This battery weighs 80 pounds, with a 10-inch by 10-inch footprint and a volume of 1350 cubic inches (including connector and hold-down bar). Both vented and sealed (valve-regulated) versions are available.

Environmental Impact. Lead, the major constituent of the lead-acid battery, is a toxic (poisonous) chemical. As long as the lead remains inside the battery container, no health hazard exists. Improper disposal of spent batteries can result in exposure to lead, however. Environmental regulations in the U.S. and abroad prohibit the disposing of lead-acid batteries in landfills or incinerators. Fortunately, an extensive infrastructure exists for recycling lead-acid batteries. Approximately 95 percent of batteries produced in the U.S.A. are recycled. The recycling process recovers all materials in the battery (lead, plastic, and sulfuric acid) for re-use in making batteries and other products. The recycling process is profitable enough that a nominal credit (approximately \$0.05 per pound) normally can be given for scrap lead-acid batteries.

Supportability. Lead-acid batteries need to be recharged immediately after discharging; therefore, a dedicated charging source is required. Constant voltage charging is the preferred method for lead-acid batteries. Suitable charging sources include generators, alternators, and transformer-rectifiers. If the voltage regulation is not controlled sufficiently, however, the battery will be overcharged or undercharged, causing premature failure. Thus, a regulated voltage source is necessary to achieve acceptable battery life. Some charging sources use voltage regulators that compensate, either manually or automatically, for the battery temperature by

increasing the voltage when cold and decreasing the voltage when hot. Adjusting the charging voltage in this manner prolongs the battery's service life at high temperature and achieves faster recharge at low temperatures.

Periodic maintenance and/or capacity checks of lead-acid batteries are required to assure reliable operation. For vented-cell batteries, electrolyte topping must be performed on a regular basis to replenish the water loss that occurs during charging. Maintenance intervals typically are two to four months. A capacity test or load test usually is included as part of the check-out procedure. For maintenance-free and valve-regulated batteries, water replenishment obviously is unnecessary, but periodic load or capacity checks generally are recommended.

The service life of a lead-acid battery depends on its type of use (e.g., rate, frequency, and depth of discharge), environmental conditions (e.g., temperature and vibration), charging method, and the care with which it is maintained. Service lives can range from one to five years, depending on the severity of the application.

Lead-acid batteries must be stored in the charged state. If allowed to remain in the discharged state for a prolonged time period, the battery becomes damaged by "sulfation." Sulfation occurs when lead sulfate forms into large, hard crystals, blocking the pores in the active material. The sulfation creates a high impedance condition that makes it difficult for the battery to accept recharge. The sulfation may or may not be reversible, depending on the specific cell design.

Conventional vented batteries normally are supplied in a dry, charged state (i.e., without electrolyte), which allows them to be stored indefinitely. Once activated with electrolyte, periodic charging is required to overcome the effect of self-discharge and to prevent sulfation. The necessary charging frequency depends on the storage temperature. At room temperature 77 F (25 C), charging every 30 days typically is recommended. More frequent charging is necessary at higher temperatures, (e.g., every 15 days at 95° F [35° C]) and less frequent charging is necessary at low temperatures (e.g., every 120 days at 50° F [10° C]).

Valve-regulated and maintenance-free batteries can only be supplied in the activated state (i.e., with electrolyte), so storage provisions are more demanding compared with dry

charged batteries. As in the case of activated VRLA batteries, periodic charging is necessary to overcome the effects of self-discharge and to prevent sulfation. The rate of self-discharge of lead-acid batteries varies widely from manufacturer to manufacturer, so the necessary charging frequency also varies widely. For example, recommended charging frequencies can range from 3 to 24 months.

User Needs. Most Air Force bases have shop facilities for storing and servicing lead-acid batteries. No special training requirements are expected if lead-acid batteries are used for the MASS application. Safety considerations associated with lead-acid batteries include spills of sulfuric acid, potential explosions from the generation of hydrogen and oxygen, short circuiting of battery terminals, and the generation of toxic gases such as arsine and stibine. These potential problems can be handled effectively with proper precautions.

Affordability. Lead-acid batteries are the least expensive of all rechargeable batteries. A typical 12-volt automotive battery, for example, costs approximately \$50. A 24V/30Ah battery typically used in AGE applications costs \$125 for vented types and \$350 for sealed (valve-regulated) types.

Nickel-Cadmium.

Operational Parameters. The cell of a nickel-cadmium battery contains an anode of cadmium (Cd), a cathode of nickel oxyhydroxide (NiOOH), and an electrolyte of potassium hydroxide dissolved in water. The electrolyte in a nickel-cadmium cell contains 31 percent (by weight) potassium hydroxide (KOH) dissolved in water. This electrolyte is highly conductive, which contributes significantly to the excellent high rate capability of nickel-cadmium batteries.

There are two basic cell types: vented and recombinant. Vented cells have a flooded electrolyte, and the hydrogen and oxygen gases generated during charging are vented from the cell container. The loss of gases causes the electrolyte level to drop over time, so periodic maintenance is required to replenish the water. Recombinant cells have a starved electrolyte, and the oxygen generated during charging diffuses from the positive electrode to the negative electrode where it recombines to form water. The recombination reaction suppresses hydrogen

evolution at the negative electrode, thereby allowing the cell to be sealed. Unlike VRLA cells, recombinant nickel-cadmium cells are sealed with a vent valve that releases only during abusive conditions. Thus, these cells remain sealed under normal charging conditions. However, provisions for gas escape must still be provided when designing battery cases because abnormal conditions may be encountered periodically (e.g., in the event of a charger failure that causes an overcurrent condition).

Evaluation Based on:

Performance. Nickel-cadmium batteries, like lead-acid batteries, normally are rated at room temperature (25° C) and operate best around this temperature. Exposure to low ambient temperature results in performance decline and exposure to high ambient temperatures results in shortened life. Typical operating temperature limits are -40° F to +122° F (-40° C to +50° C).

Like the lead-acid battery, the peak power available from a nickel-cadmium battery depends mainly on its internal impedance. High rate cells are designed specifically to have very low internal impedance as required for starting engines and APUs. The peak power density for these types of batteries can be as high as 600 W/kg at room temperature. At lower temperatures, the peak power capability drops considerably. At 0° F for instance, a derating factor of 70 percent is typical (i.e., 420 W/kg). Thus, for cold start applications, the nickel-cadmium battery out-performs the lead-acid battery.

Deployability. Nickel-cadmium batteries are available in a wide variety of size and form factors. A common battery used in AGE is rated at 24V/30Ah. This battery weighs 80 pounds, with a 10-inch by 10-inch footprint and a volume of 1270 cubic inches (including connector and hold-down bar). This battery is a vented-cell design. A maintenance-free, sealed-cell design is available with the same footprint that weighs 90 pounds.

Environmental Impact. Cadmium, a major constituent of the nickel-cadmium battery, is a toxic (carcinogenic) chemical. As long as the cadmium remains inside the battery container, no health hazard exists. Improper disposal of spent batteries can result in exposure to cadmium,

however. In the U.S. and abroad, spent nickel-cadmium batteries are considered to be hazardous waste, and their disposal is strictly regulated. Several metallurgical processes have been developed for reclaiming and recycling the nickel and cadmium from nickel-cadmium batteries. These processes can be used for both vented and sealed cells. Unlike lead-acid batteries, which can be sold for their scrap value, scrap nickel-cadmium batteries require a cost expenditure for disposal. The disposal cost averages about \$1.75 per pound.

Supportability. Nickel-cadmium batteries generally require a more sophisticated charging system than lead-acid batteries, especially in the case of sealed-cell designs. Dedicated chargers with constant current or pulsed current typically are used. The key requirement is to strike an optimum balance between overcharging and undercharging, while achieving full charge in the required time frame. Overcharging results in excessive water loss (vented cells) or heating (sealed cells). Undercharging results in capacity fading. Some overcharge is necessary, however, to overcome coulombic inefficiencies associated with the electrochemical reactions.

One peculiarity associated with nickel-cadmium batteries is the so-called "memory effect." The memory effect reduces the available capacity if the battery is not discharged completely before recharging. For example, if batteries are discharged several times to only half capacity, they will lose the capability to be discharged past that point. When used only for peak power delivery, the memory effect generally is of little consequence.

Maintenance requirements for vented-cell batteries are more extensive than for lead-acid batteries. Procedures include cell reconditioning, isolating and replacing faulty cells, and cleaning to remove corrosion and carbonate build-up. These procedures are labor intensive and require a dedicated shop facility.

The service life of a nickel-cadmium battery depends on many factors, including its type of use it experiences (e.g., rate, frequency, and depth of discharge), environmental conditions (e.g., temperature and vibration), charging method, and the care with which it is maintained and reconditioned. Thus, it is difficult to generalize the expected service life. All things considered, the service life of a nickel-cadmium battery is inherently longer than that of a lead-acid battery. In terms of cycle life, a nickel-cadmium battery generally can last 500 to 1000 cycles at 80

percent depth of discharge per cycle, which is two to four times higher than that of lead-acid batteries. However, the longer life is at the expense of a higher unit price.

Nickel-cadmium batteries can be stored in any state of charge and over a broad temperature range (e.g., -85° F to +140° F [-65° C to +60° C]). For maximum shelf life, however, it is best to store batteries between 32° F and 86° F (0° C and 30° C). Vented-cell batteries are normally stored with the terminals shorted together. Shorting of sealed-cell batteries during storage is not recommended, however, since it may cause cell venting.

When left on open circuit during periods of non-operation, nickel-cadmium batteries will self-discharge at a relatively fast rate. As a rule of thumb, the self-discharge rate is approximately 1 percent per day at 20° C, and the rate increases by 1 percent per day for every 18° F (10° C) rise in temperature (e.g., 2 percent/day at 86° F [30° C], 3 percent/day at 104° F [40° C], etc.). The capacity lost by self-discharge is fully recoverable when charged in the normal fashion.

User Needs. Most Air Force bases have shop facilities for storing and servicing nickel-cadmium batteries. No special training requirements are expected if nickel-cadmium batteries are used for the MASS application. The same safety precautions discussed under lead-acid batteries also apply to nickel-cadmium batteries, except the generation of poisonous gases (arsine and stibine) is not possible.

Affordability. Nickel-cadmium batteries are significantly more expensive than lead-acid batteries. A typical 24V/30Ah, vented-cell battery used in AGE costs approximately \$1000. Replacement cells cost about \$50 each. Sealed-cell batteries cost two to three times the cost of vented-cell batteries due to low production volume.

Ultracapacitors.

Operational Parameters. Energy is stored in an ultracapacitor by charge separation within the micropores of a very high surface area electrode material that is impregnated with electrolytes. The charge storage occurs by orientation of ions at the liquid-solid interface

(capacitive storage) and by electrochemical transfer reactions (pseudocapacitance). The internal construction of an ultracapacitor is similar to that of a bipolar battery consisting of a stack of bipolar electrodes, separators, and electrolytes. Ultracapacitors with the highest power density utilize thin titanium substrates coated with ruthenium oxide and an electrolyte of sulfuric acid and water. As in the case of lead-acid batteries, the high conductivity of sulfuric acid permits high discharge rates to be obtained. Close spacing of electrodes gives ultracapacitors a rate capability that surpasses even high-rate battery designs.

Evaluation Based on:

Performance. Peak power densities of 2500 W/kg have been achieved with an energy storage density of 6 Wh/kg and 9 Wh/L. This peak power capability is about five times greater than high-rate nickel-cadmium batteries. However, the discharge profile of an ultracapacitor resembles that of a capacitor rather than a battery. In a capacitor, the voltage drops rapidly as energy is removed ($E = CV^2$). This drop in voltage causes the power output to drop rapidly during discharge, and needs to be taken into account when sizing for peak power applications.

Deployability. The use of ultracapacitors as a part of a battery/ultracapacitor hybrid design would result in a lighter, more compact power source for starting engines and other peak power applications. A weight and volume reduction of twofold or more is projected. The rate of self-discharge of an ultracapacitor is relatively high, so a method of charging must be provided prior to use. A battery with high energy density can supply the energy for charging the ultracapacitor.

No standard sizes or form factors have been developed for ultracapacitor devices. PRI has developed a prototype 100-volt, 0.7 Wh device that weighs 1.45 pounds and has a volume of 12 cubic inches. Maxwell has developed a prototype 3-volt, 2.6 Wh device that weighs 1.0 pound and has a volume of 18 cubic inches.

Environmental Impact. Ultracapacitors do not contain toxic chemicals, but the electrolyte can be corrosive (e.g., sulfuric acid). Spent ultracapacitors containing costly metals (e.g., titanium or ruthenium) will need to be collected to recover the metal content.

Supportability. Specific storage and maintenance requirements are unknown at present. Devices are completely sealed and should have characteristics similar to conventional capacitors.

User Needs. Ultracapacitors are a new technology with no operational experience in the military. Special training requirements will need to be defined. Safety precautions will be necessary due to their extreme high-rate capability.

Affordability. Due to the limited availability of ultracapacitors, the cost of these devices is very high and difficult to estimate. Cost goals for mature, high volume production are \$500 to \$1000 per kWh. Significant development costs can be expected.

3.2.9.3 Comparison and Summary

Table 12 compares the advantages and disadvantages of the candidate battery and ultracapacitor technologies. The main tradeoff is peak power density versus cost. The technologies with higher peak power capability generally have a higher cost. The notable exception to this trend is the TMF lead-acid battery, which has a higher peak power capability than nickel-cadmium, but a lower projected unit cost. This battery type is not yet available in the required size range, however, so a modest development cost can be expected.

A secondary tradeoff consideration is the use of vented versus sealed cells. Vented-cell batteries cost less, but maintenance costs are higher. In general, the life-cycle cost is lower with sealed, maintenance-free batteries.

Table 12. Battery Evaluation Summary

Battery Type	Advantages/Strengths	Disadvantages/Weaknesses
Vented Lead-Acid	Commercially available Low purchase cost Easily recycled	Maintenance burden Peak power density inferior to nickel-cadmium, especially at low temperature
Sealed Lead-Acid	Commercially available Low purchase cost, but not as low as VLA Maintenance-free Easily recycled	Peak power density inferior to nickel-cadmium, especially at low temperature
TMF Lead-Acid	Peak power density far surpasses nickel-cadmium Low purchase cost, but not as low as VLA Maintenance-free	Limited availability Modest development cost
Bipolar Lead-Acid	Peak power density surpasses nickel-cadmium Maintenance-free	Limited availability Modest development cost Purchase cost much higher than other lead-acid batteries
Vented Nickel-Cadmium	Commercially available Peak power density surpasses most lead-acid batteries, especially at low temperatures Maintenance-free Long service life	High purchase cost Maintenance burden Modest disposal cost
Sealed Nickel-Cadmium	Peak power density surpasses most lead-acid batteries, especially at low temperatures Maintenance-free Long service life	Limited availability High purchase cost Modest disposal cost
Ultracapacitor	Peak power density surpasses all battery types Maintenance-free Long service life Hybrid operation with a primary power source may reduce overall size and weight of system	Limited availability High development cost High purchase cost

3.2.10 System Control

The purpose of the system control function is to monitor and direct the operation of the MASS system. For any critical piece of equipment it is necessary to ensure that repairs can be made quickly and that essential maintenance can be performed with minimum system down-time. Therefore, a major task of the system control is to identify any failure conditions so corrective action may be taken. There are basically four levels of fault monitoring: manual troubleshooting, hardware monitoring, built-in-test (BIT) detection, and BIT isolation. Between these levels are various combinations of fault monitoring that are dependent on the level of complexity of the design, operator's experience, and critical importance of the equipment. Current AGE uses BIT in certain cases, but overall, very little BIT is included.

3.2.10.1 Applicable Techniques

Manual Troubleshooting. Manual troubleshooting represents no additional equipment to assist in the identification of a failure. It relies exclusively on the expertise of the operator. Due to the critical nature of the system and the experience of the operator, manual troubleshooting as the only means of fault monitoring is not appropriate for the MASS program.

Hardware Monitoring. Hardware monitoring represents the minimum fault detection for the MASS program. It is discussed in detail in the following section.

BIT Detection. BIT detection is an automated diagnostic routine that identifies the fault to the a component or group of components. It is discussed in the following section.

BIT Isolation. BIT isolation is an automated diagnostic routine that identifies the fault to the line replaceable unit (LRU). It is discussed in the following section.

3.2.10.2 Description of Candidate Techniques

Hardware Monitoring.

Operational Parameters. Hardware monitoring consists of observing certain critical operating characteristics to determine whether the system is performing correctly. This approach represents a minimum complexity design and relies heavily on the experience and diagnostic capability of the operator.

The hardware monitoring circuitry will consist of various types of transducers, a monitor circuit, and an operator display. The purpose of the transducer is to generate an electrical signal that is proportional to the system parameters being monitored. These parameters could be temperature, pressure, velocity, voltage, etc. The monitor circuit compares the outputs of each transducer against a predefined response. The status of each of these comparisons is sent to the operator display. In the event of a failure, the operator is notified of the deviation in performance.

This level of fault monitoring will identify what parameter deviated from its normal operating condition, but it may not identify the actual failed item. It will be the task of the operator to trace the cause of the problem.

Evaluation Based on:

Performance. Hardware monitoring has only a limited capability to trace a failure to the component level. A high level of training will be required of the user to trace the failure to the LRU level.

Deployability. Hardware monitoring can be implemented easily in the MASS system.

Environmental Impact. No hazardous materials are expected to be needed for hardware monitoring.

Supportability. The maintenance time of the system will be high because of the added time to identify the failure to the LRU level.

User Needs. Hardware monitoring supplies minimum information to the user to identify the cause of the failure condition.

Affordability. Due to the simplicity of the technique, development costs will be low.

Built-in-Test (BIT) Detection.

Operational Parameters. BIT detection automates the fault monitoring of a system. Complex electronic systems such as laboratory instruments, avionics, and process electronic systems now frequently include BIT facilities. BIT consists of additional hardware and often software that is used for carrying out functional tests on the system. It can be very effective in increasing system availability and user confidence in the system.

The BIT detection circuitry will consist of various types of transducers, a microprocessor controller, and an operator display. The purpose of the transducer is to generate an electrical signal that is proportional to the system parameter being monitored. This parameter could be temperature, pressure, velocity, voltage, etc. The microprocessor controller compares the output of each transducer against a predefined response. In the event of a failure, the operator is notified.

The difference between BIT detection and hardware monitoring is the number of parameters being monitored and the automating of the process. Because the system is now automated, a larger number of signals can be monitored. As a result, the system will be better able to identify the failed component or group of components. This allows the operator to be less familiar with the actual operation of the system.

Evaluation Based on:

Performance. BIT detection has moderate to high capability to trace a failure to the component or group of components level. A moderate level of training will be required of the user to trace the failure to the LRU level.

Deployability. Because BIT detection is passive fault monitoring, it can be integrated easily into the system. Incorporation of BIT will increase the design effort because of the additional circuitry needed.

Environmental Impact. No hazardous materials are expected to be needed for BIT detection.

Supportability. Maintenance time of the system will be moderate to low because BIT detection will identify the failure to a group of components.

User Needs. BIT detection will be able to inform the user of the failure and identify the most likely components to have caused the failure.

Affordability. Because BIT detection can be added easily to the system, development costs will be moderate.

Built-in-Test (BIT) Isolation.

Operational Parameters. BIT isolation is an automated diagnostic routine that identifies a fault to the LRU. Typically, it is used in conjunction with BIT detection. BIT detection identifies a failure, during normal operation, to a group of components. BIT isolation places the system into a special operating mode to identify the failure to the LRU.

BIT isolation circuitry is similar to BIT detection except for its complexity. While BIT detection is a passive monitoring device, BIT isolation has the capability to effect the system response. In many cases, identifying the failure to the LRU is difficult during normal operation because of external forces on the system. BIT isolation removes those signals and injects its own, thereby determining the response of each subassembly.

The advantage of this technique is that it requires the operator to have only a minimum understanding of the system. The system informs the operator what component needs to be repaired. The disadvantages are the cost and level of complexity required in the design to identify a failure to the component level.

Evaluation Based on:

Performance. BIT isolation has a high capability to trace a failure to the LRU level. A minimum level of training will be required of the user to trace the failure to the LRU level.

Deployability. Because BIT isolation is an integrated part of the entire design, it must be a significant portion of the design effort. The ability to detect a failure to a component may affect the selection or design of the various LRUs. Therefore, BIT isolation can effect the deployability of the MASS because of parts requirements. However, its overall size should be small compared to the other components of the MASS.

Environmental Impact. No hazardous materials are expected for BIT isolation.

Supportability. Maintenance time of the system will be minimum because of the fast diagnostic response. However, the increased complexity of the design will increase the likelihood of a failure in the BIT circuitry.

User Needs. BIT isolation will inform the user of a failure to the LRU.

Affordability. Because of the complexity of the circuitry, development costs will be significantly higher than for the other techniques.

3.2.10.3 Comparison and Summary

The actual technique chosen for the MASS program will be dependent upon the final requirements of the system. Because the MASS program will consist of a collection of separate support equipment integrated together, the BIT detection technique appears to be the likely choice. However, BIT systems have been costly and unreliable when applied to aircraft. Some

limited BIT features will be helpful to MASS but should not be a complex and expensive system (see Table 13).

Table 13. System Control Evaluation Summary

Fault Techniques	Advantages/Strengths	Disadvantages/Weaknesses
Manual Troubleshooting	No cost No complexity	Longest maintenance time Requires highest level of training
Hardware Monitoring	Identifies failure conditions Minimum cost approach Minimum complexity approach	Requires long maintenance time Requires high degree of training Additional sensor hardware required
BIT Detection	Identifies failure to component or group of components Moderate cost approach Moderate complexity approach	Requires moderate maintenance time Requires moderate degree of training Hardware complex.
BIT Isolation	Identifies failure to component (LRU) Minimum maintenance time Minimum training	Highest complexity approach Significantly high cost approach

3.2.11 Engineering Materials

The engineering materials considered for MASS are mainly structural materials used in the frame and running gear, which support the other equipment and facilitate mobility. The use of special materials in each separate technology is considered under that particular technology. Current AGE uses primarily steel and aluminum for structural materials.

3.2.11.1 Applicable Technologies

Plastics and Composites. Plastics are synthetic materials made from chemical raw materials called monomers. Composites are any material reinforced with another material.

However, for MASS, structural plastics, plastic composites, plastic laminates, and structural foam were considered. Structural plastics and composites are used for large housings and hollow shapes such as boat hulls, equipment shrouds, housings for large appliances and communication equipment, materials handling containers, pressure vessels, and tanks.

Elastomers and Rubbers. These materials generally are defined as any material capable of extreme deformability with more or less complete recovery upon removal of the deforming force. Besides natural rubber obtained from a rubber tree, this includes materials such as neoprene, nitrile, styrene butadiene, and butadiene rubber. These materials are used for shock absorption; noise and vibration control; sealing; corrosion, abrasion, and friction protection; electrical and thermal insulation; waterproofing; confining other materials; and load bearing. Some or all of these functions may be needed in MASS, but are likely to be an insignificant part of the total system. Any other technology can use these materials as needed to provide improvements in their performance. However, these materials will not be used as a major structural component and will not be considered further for MASS.

Nonferrous Metals. Nonferrous metals include any metal that is not iron-based. For MASS, the structural nonferrous metals considered include aluminum, beryllium, copper, magnesium, nickel, refractory metals such as tungsten and molybdenum, tin, titanium, zinc, and zirconium.

Ferrous Metals. Ferrous metals are all iron-based alloys including cast iron, carbon steel, alloy steel, stainless steel, and other specialty steels. These are the traditional structural materials for AGE and are also strong candidates for MASS.

Other Engineering Materials. Any materials not in the above categories are collected within this category. For example, engineering ceramics, special fibers, glass, manufactured carbon, and refractory hard metals are included in this group.

3.2.11.2 Description of Candidate Technologies

Plastics and Composites.

Operational Parameters. Plastics and composites are used where lightweight, chemical resistance, electrical insulation, durability, or transparency characteristics are required. By adding glass or other fibers to the plastic matrix, the resulting composite parts can attain high strength characteristics as well. However, plastic and composite parts are manufacturing-intensive in that they require specialized manufacturing systems. These include molds, presses, autoclaves, fiber winding machines, and furnaces. As a result, parts made of plastic typically have a high initial cost and become inexpensive only after a large number of parts have been made.

The design of plastic parts, therefore, has to include provisions for these special manufacturing systems and the resulting differences in part characteristics. For example, the strength of a molded part is significantly affected by such processing characteristics as direction of flow, pressure during molding, melt temperature, thermal degradation, cooling rate, and stress concentrations. As a result, the design cost of plastic parts is also high.

In general, plastic and composite materials can provide special characteristics for mechanical parts which make them advantageous. However, the up-front costs of these parts can be high, so large production runs are usually required to make them cost-effective.

Evaluation Based on:

Performance. Plastics, and especially composites, have the strength and environmental resistance required for MASS structural components. Doors and covers for MASS would be effective if manufactured from composite materials. Plastics and composites can be selected with high resistance to battle damage as well as nuclear, biological, and chemical (NBC)

decontaminants and agents. New plastics and composites are being developed daily for specialized applications, and these developments should be monitored for any new materials.

Deployability. Plastics and composites are lightweight for a given volume. However, to obtain the desired strength, most of these materials require thicker parts approaching the weight of steel parts. No significant difference in weight or size should be expected in building a MASS with plastic parts as opposed to steel parts.

Environmental Impact. Plastic and composite parts are very environmentally benign once they are fabricated. However, fabrication of these materials can be detrimental to the environment through the release of solvents, molding compounds, and scrap materials. These environmental problems have long been recognized by plastics manufacturers and have been controlled adequately in most cases. Plastic parts can be recycled, but composites usually cannot.

Supportability. Typically, plastic and composite parts, if correctly designed, are highly reliable. Sometimes, however, plastic parts will fail prematurely because the operating environment is more strenuous than anticipated. For example, an open plastic door may be blown by the wind and break off at the hinges. A metal door might simply bend, allowing it to be bent back and reused. If designed with sufficient strength at the hinge joint, the plastic door might bend and return to its original shape after the wind load is removed. Maintainability and modularity of a plastic part should be no different from any other material.

User Needs. Plastics and composites should meet all of the users' needs in human factors and safety.

Affordability. Plastics and composites typically are more expensive than metal parts in small quantities because of the development costs. However, this is highly dependent upon the quantity of parts procured and the complexity of the parts. Plastic parts are also fabricated by fewer manufacturers than are metal parts. For MASS, assuming maximum quantities of 1000 for any given part, and assuming that the parts will be flat panels or doors, the cost of the plastic part will likely be similar to the cost of a steel part.

Elastomers and Rubbers. These materials will not be considered because they are not structural materials.

Nonferrous Metals.

Operational Parameters. Of the nonferrous metals, the only candidate inexpensive enough for use as a structural material in MASS is aluminum. Others, such as beryllium and magnesium, will not be considered because of their high cost. Aluminum is available in structural forms such as I-beams, angle, or tubing and can be welded fairly easily into complex structures. It has a high strength-to-weight ratio and good corrosion resistance. It is also nonsparking and nonmagnetic.

Evaluation Based on:

Performance. Aluminum alloys have fairly high strengths, especially when heat-treated. They have good corrosion resistance and can be coated with a variety of materials to improve their resistance to the environment. Aluminum has a high coefficient of thermal expansion, which can be troublesome for equipment exposed to wide temperature ranges. However, aluminum maintains or increases in strength at low temperatures and maintains good ductility at these temperatures. Aluminum is susceptible to corrosion by some NBC decontaminants, but can be coated to prevent serious problems. Aluminum has a long and successful history of use in the aerospace industry and will continue to provide the basis for aircraft structures for many years.

Deployability. Aluminum is a high strength- to -weight material that would be excellent for use on MASS. The size and weight of aluminum structures are relatively low for their cost.

Environmental Impact. Aluminum is environmentally benign and safe for use in almost any environment. The manufacture of the material results in some effluents that are well-understood and controlled.

Supportability. Reliability and maintainability of the structures built with aluminum are much higher than for any of the mechanical equipment of a MASS. Modular components and systems can be built easily using aluminum parts.

User Needs. Aluminum parts currently are used to meet the user needs on many similar items and are quite safe for this use.

Affordability. Aluminum is about three times as expensive as steel for structural applications. Welding is a more technically challenging operation in aluminum than steel, but is commonly done. Because of its good corrosion resistance, it can have longer life than steel in some applications.

Ferrous Metals.

Operational Parameters. Of the various iron alloys possible as the structural material for MASS, carbon steel is the most likely. Alloy steels, stainless steels, and other specialty steels provide improvements in properties such as strength, hardness, or corrosion resistance. However, these materials are more expensive and harder to fabricate. Cast iron has good corrosion resistance, but can be brittle and susceptible to fracture. Cast iron is used for very heavy structural components, but is rarely used for vehicular components because of its weight.

Evaluation Based on:

Performance. Ferrous metals are an excellent choice for use as the structural materials for MASS. Some types have better characteristics than others in the areas of corrosion, temperature stability, strength, hardness, ductility, or coatability, but carbon steel appears to have the best combination of characteristics in this class for MASS. It has a good strength-to-weight

ratio, is easily coated for corrosion resistance, and is resistant to NBC agents and decontaminants, especially when coated. Carbon steel is the most common structural material for equipment such as MASS and is easily welded or fastened together.

Deployability. Carbon steel is the current material for many structural components of AGE and would be a good choice for MASS. Its strength-to-weight and strength-to-volume ratios are good. However, its total weight can be higher than aluminum or composite materials.

Environmental Impact. Iron and steel components have been fabricated for many years and are quite environmentally safe. The only environmental concern is the use of coal as the heat source for smelting during the fabrication of the materials. Current facilities and equipment have been introduced to eliminate this problem, and steel materials are widely manufactured and used.

Supportability. The reliability and maintainability of steel parts are generally very good. Some corrosion can occur if the parts are left uncoated to the point of failure in extreme cases. However, coating technologies including paints and galvanizing techniques have improved, and steel parts can have long life and high reliability in any environment. Steel can be used for modular designs and to provide high availability of the system.

User Needs. Steel parts can meet all of the human factors and safety needs of the users.

Affordability. Steel parts are the least expensive alternative to a structural material for MASS. Development and procurement costs are low due to the vast amount of steel parts used in industry today. Steel is available in a multitude of common shapes, is easily fabricated and assembled, and is easily maintained with coatings and paints for long life.

Other Engineering Materials.

Operational Parameters. In addition to the materials listed above, other materials such as ceramics, carbon, and glass are being used as structural materials. Combinations of such materials in the form of laminates, composites, fiber-reinforced metals, and fiber matrices of various types are especially prevalent. Many of these materials provide special capabilities such

as good performance at high temperatures, in corrosive atmospheres, and under high load conditions. However, high cost and long-term reliability are problems with these materials.

Evaluation Based on:

Performance. These other engineering materials mentioned above can provide the strength and corrosion resistance necessary for MASS. However, the manufacture of these materials can be difficult and costly. Many of these materials are brittle and susceptible to impact damage. Extreme environments, especially high temperatures, are handled easily by many of these materials. In the long term, these materials may become more prevalent, but currently they are used only in special cases.

Deployability. These materials generally are lighter weight and of less volume than steel parts of equal strength. Careful handling of these materials is required due to lower impact resistance.

Environmental Impact. These materials are good environmentally, but generally are new materials with unknown environmental considerations. Manufacture of the composite materials can involve the use of solvents and molding compounds which can be environmentally hazardous.

Supportability. Because these materials are either new or are new combinations of materials, their reliability and long-term performance are unknown. The effects of temperature cycles, fatigue, and long-term exposure to chemicals could cause unexpected failures. Maintainability and modularity of these parts are probably the same as other, more common materials.

User Needs. Human factors and safety characteristics of these materials are good and allow the user to have complete confidence in working with them.

Affordability. These materials generally are higher in cost than other materials such as steel and aluminum. The manufacturing and design costs are greater due to the more complex manufacturing processes required and the unknown engineering characteristics of the materials.

Operational costs should be the same, but the life-cycle costs will be higher due to the increased up-front costs and the costs of the unknown reliability of the materials.

3.2.11.3 Comparison and Summary

The structural components of the MASS will need to provide sufficient strength to support the other components. Almost any material could perform this function, but those with the higher strength-to-weight ratios will provide the lightest and smallest configuration. In addition, the cost of the parts should be low and the reliability high to meet the needs of MASS. With this combination of requirements, the best candidates are carbon steel and a high strength aluminum alloy. These materials are low cost, highly reliable, and easily manufactured for modularity and maintainability (see Table 14).

Table 14. Engineering Materials Evaluation Summary

Engineering Materials	Advantages/Strengths	Disadvantages/Weaknesses
Plastics and Composites	Light weight, good corrosion resistance	High low- volume cost, difficult to manufacture
Nonferrous Metals	Moderate weight, good corrosion resistance	Moderate cost
Ferrous Metals	Easily manufactured, easily coated, low cost	Heavy weight
Other Engineering Materials	Good corrosion resistance, other special properties	High cost, unknown reliability

4.0 Recommendations

As described in the previous sections of this report, the engineering domains encompassing ground support equipment contain a wide variety of technologies which could be used for MASS. As a result of the evaluations conducted during this program, the following recommendations can be made for technologies to be incorporated into a MASS design.

4.1 Engines

The choice of engines for the primary source of power for MASS can be limited to two: a turbine engine or a diesel engine. However, it is difficult to compare these two because the turbine provides low-pressure compressed air as well as shaft power for operation of the MASS. This compressed air can be used for input to an air cycle air conditioning system. However, an air cycle air conditioner is not as efficient as a vapor compression air conditioning system, which can be connected directly to a diesel engine. The comparison, then, is a turbine engine/air cycle air conditioner to a diesel engine/vapor compression air conditioner.

The advantage of the turbine/air cycle system is its light weight and somewhat smaller size. However, the turbine is up to 10 times as expensive as the diesel for the same horsepower output. The diesel is twice as heavy but uses much less fuel. Therefore, for the same output and work cycle, the diesel with its fuel tank can be smaller than the turbine and its fuel tank. The choice of turbine versus diesel can be made only when all of the criteria for MASS have been identified.

4.2 Motors

The best candidate for the MASS electrical motors is the AC induction motor. These motors are rugged, relatively inexpensive, and reliable. For some low power level requirements, a single phase AC motor may be used where the induction motor is too inefficient. However, in most high power applications, the induction motor is the best candidate.

4.3 Air Conditioning Equipment

The selection of an air conditioning technology for MASS is highly dependent upon the selection of the engine technology. As stated in paragraph 4.1, if a turbine engine is selected, the air cycle air conditioning system is best. However, if a diesel engine is selected, then the vapor compression system is best.

In general, the air cycle system is less efficient and requires more power and equipment to obtain the same output as the vapor compression system. When using a turbine engine, however, with a built-in compressor discarding compressed air, it makes more sense to use the air cycle system.

4.4 Energy Conversion

For the primary energy conversion method for powering AGE, the best technology appears to be the synchronous AC generator. This system will generate AC power compatible with the AC induction motor, which is the recommended motor for MASS. Should DC power be required for any reason, an AC to DC converter could be used. These generators are reliable, require minimal starting torque, and are commonly used throughout industry.

4.5 Hydraulic Pumps

The recommended hydraulic pump for MASS is the piston pump. This type of pump can provide the required fluid flow and pressure to maintain any aircraft. Although it is somewhat higher in cost than other pumps, its reliability and efficiency will make up for the higher initial cost.

4.6 Air Compressors

To meet the high pressure needs of MASS, a positive displacement air compressor must be used. Of the technologies studied, the best positive displacement compressor is the reciprocating piston compressor. These compressors are used commonly throughout industry and are easily maintained and reliable. These compressors are subject to vibration, but are compact for the pressures desired.

4.7 Floodlights

The lamps used in current AGE include mercury vapor and high-pressure sodium. However, the mercury vapor lamps are less efficient and are being replaced by high-pressure sodium lamps. No other technology was found that provided the efficiency, life, and reliability of the high pressure sodium lamps. For these reasons, they are recommended for MASS.

4.8 Nitrogen Generation

Nitrogen can be supplied from cylinders that are refilled as needed, or the nitrogen can be separated from air at the MASS. For the amounts of nitrogen used in maintaining aircraft, a generating system within the MASS makes sense. The initial cost of the system is higher than the cost of storage bottles, but a generating system will still be required to fill them. Transportation of the bottles to the flight line then becomes a problem.

Of the nitrogen generation systems, the hollow fiber membrane is the best for MASS. These are continuous flow systems with high reliability. A compressor will be needed to provide the input air and to pressurize the nitrogen for use in the aircraft.

4.9 Batteries

The recommended battery for MASS is the sealed, maintenance-free thin metal film lead-acid battery. These batteries currently are not available in the size needed for MASS, but appear to have the best combination of peak power and lowest unit cost. Some development will be required to increase the size of these batteries, but they will have lower life cycle costs than other types.

4.10 System Controls

The MASS will be designed for ease of maintenance and high reliability. For these reasons, BIT systems may prove to be more costly than they are worth. Current equipment, such as engines or compressors, can be purchased with some BIT capability. This will likely be the extent to which BIT will be used in MASS, as support for maintenance of individual items within the system. A complete MASS BIT will likely be too costly and will not improve the system maintainability sufficiently to warrant it.

4.11 Engineering Materials

The recommended structural materials used to fabricate MASS are carbon steel coated for corrosion protection and aluminum alloys. These materials are used on the current AGE and provide excellent strength-to-weight characteristics. Primarily, however, they are low-cost materials that are the best-suited for structural applications such as in MASS.

Appendix A

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